Molecular Gas in NUclei of GAlaxies (NUGA)

XIV. The barred LINER/Seyfert 2 galaxy NGC 3627 *

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Abstract. We present 12CO(1–0) and 12CO(2–1) maps of the interacting barred LINER/Seyfert 2 galaxy NGC 3627 obtained with the IRAM interferometer at resolutions of 2′′ × 1′′ and 0′′ · 9 × 0′′ · 6, respectively. We also present single-dish IRAM 30 m 12CO(1–0) and 12CO(2–1) observations used to compute short spacings and complete interferometric measurements. These observations are complemented by IRAM 30 m measurements of HCN(1–0) emission detected in the center of NGC 3627. The molecular gas emission shows a nuclear peak, an elongated bar-like structure of ~18″ (~900 pc) diameter in both 12CO maps and, in 12CO(1–0), a two-arc spiral feature from r ~9″ (~450 pc) to r ~16″ (~800 pc). The inner ~18″ bar-like structure, with a north/south orientation (PA = 14°), forms two peaks at the extremes of this elongated emission region. The kinematics of the inner molecular gas shows signatures of non-circular motions associated both with the 18″ bar-like structure and the spiral feature detected beyond it. The 1.6 μm H-band 2MASS image of NGC 3627 shows a stellar bar with a PA = 21°, different from the PA (14°) of the 12CO bar-like structure, indicating that the gas is leading the stellar bar. The far-infrared Spitzer-MIPS 70 and 160 μm images of NGC 3627 show that the dust emission is intensified at the nucleus and at the ansae at the ends of the bar, coinciding with the 12CO peaks. The GALEX far-ultraviolet (FUV) morphology of NGC 3627 displays an inner elongated (north/south) ring delimiting a hole around the nucleus, and the 12CO bar-like structure is contained in the hole observed in the FUV. The torques computed with the HST-NICMOS F160W image and our PdBI maps are negative down to the resolution limit of our images, ~60 pc in 12CO(2–1). If the bar ends at ~3 kpc, coincident with corotation (CR), the torques are negative between the CR of the bar and the nucleus, down to the resolution limit of our observations. This scenario is compatible with a recently-formed rapidly rotating bar which has had insufficient time to slow down because of secular evolution, and thus has not yet formed an inner Lindblad resonance (ILR). The presence of molecular gas inside the CR of the primary bar, where we expect that the ILR will form, makes NGC 3627 a potential smoking gun of inner gas inflow. The gas is fueling the central region, and in a second step could fuel directly the active nucleus.

Keywords. galaxies: individual: NGC 3627 – galaxies: spiral – galaxies: active – galaxies: nuclei – galaxies: ISM – galaxies: kinematics and dynamics

1. Introduction

The Nuclei of Galaxies (NUGA) project (García-Burillo et al. 2003) is an IRAM Plateau de Bure Interferometer (PdBI) and 30 m single-dish survey of nearby low-luminosity active galactic nuclei (LLAGN). The aim is to map, at high resolution (~0′′5-2′′) and high sensitivity (~2-4 mJy beam⁻¹), the distribution and dynamics of the molecular gas in the inner kpc of the galaxies of our sample, and to study the different mechanisms for gas fueling of LLAGN.

NUGA galaxies analyzed so far show that there is no unique circumnuclear molecular gas feature linked with nuclear activity, but rather a variety of molecular gas morphologies which characterize the inner kpc of active galaxies. We have found one- and two-armed instabilities (García-Burillo et al. 2003), well-ordered rings and nuclear spirals (Combes et al. 2004; Casasola et al. 2008a), circumnuclear asymmetries (Krips et al. 2005), large-scale bars (Boone et al. 2007, Hunt et al. 2008), and smooth disks (Casasola et al. 2010). Among these morphologies, analyzing the torques exerted by the stellar gravitational potential

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on the molecular gas shows that only four NUGA galaxies: NGC 6574 (Lind-Krieger et al. 2008), NGC 2782 (Hunt et al. 2008), NGC 3147 (Casasola et al. 2008a), and NGC 4579 (García-Burillo et al. 2009) show evidence for gas inflow. These galaxies have several features in common: (1) a large circumnuclear mass concentration (i.e., a dominant stellar bulge); (2) a high circumnuclear molecular gas fraction (≥10%); and (3) kinematically decoupled bars with overlapping dynamical resonances. The large amount of gas around the nucleus, combined with dynamical features that enable the gas to penetrate the inner Lindblad Resonance (ILR), seem to be necessary (and perhaps sufficient) ingredients for inducing gas inflow in circumnuclear scales.

The existence of different nuclear molecular morphologies can be sought in the variety of timescales characterizing nuclear activity. Strong fueling only lasts for a time of \( t_{\text{fuel}} \sim 0.002 \times t_H \), where \( t_H \sim 1.4 \times 10^8 \) yr is the age of the Universe (Heckman et al. 2004). Thus, the total time during which strong fueling can occur is around \( t_{\text{fuel}} \sim 3 \times 10^7 \) yr; if there are \( N \) fueling events per black hole per Hubble time, each event would have a duration of \( t_{\text{event}} \sim 3 \times 10^7 / N \) yr. This implies that the strong accretion phase is a fraction \( 0.3/N \) of the characteristic galaxy dynamical time (\( \sim 10^8 \) yr). Although large-scale bars can produce gas inflow (e.g., Combes & Gerin 1985; Sakamoto et al. 1999) and in some cases also drive powerful starbursts (e.g., Knapp et al. 2002; Jogee et al. 2005), a correlation between large-scale bars and nuclear activity has not yet been verified (e.g., Mulchaey & Regan 1997). This lack of correlation is probably related to the different timescales for bar-induced gas inflow (\( \geq 300 \) Myr, Jogee et al. 2005). AGN duty cycles (\( \sim 10^7 \) yr), and intermittent active accretion every \( \sim 10^8 \) yr (Ferrarese et al. 2001; Marecki et al. 2003; Janiuk et al. 2004; Hopkins & Hernquist 2006; King & Pringle 2007). The comparison of these different timescales suggests that most AGN are in an intermediate phase between active accretion episodes making the detection of galaxies with nuclear accretion somewhat difficult.

Gravitational torques act on timescales of \( \sim 10^6-7 \) yr and are the most efficient mechanism in driving the gas from large spatial scales (some tens of kpc) to intermediate spatial scales (a few hundreds of pc). Dynamical friction and viscous torques are often invoked, in addition to gravitational torques, as possible mechanisms of AGN fueling. However, dynamical friction of giant molecular clouds in the stellar bulge of a galaxy tends to be slow, inefficient process which, if to first approximation, can be neglected relative to gravity torques (García-Burillo et al. 2005). Viscous torques can be more effective, and are favored in the presence of large density gradients and high galactic shear (see García-Burillo et al. 2005, for details). Nevertheless, they are relatively inefficient when there are strong (positive) gravity torques.

This paper is dedicated to the galaxy NGC 3627, the eleventh object of the core NUGA sample studied on a case-by-case basis. NGC 3627 (Messier 66, \( D = 10.2 \) Mpc, \( H_0 = 73 \) km s\(^{-1}\) Mpc\(^{-1}\)) is an interacting (e.g., Casasola et al. 2004) and barred galaxy classified as SAB(s)b showing signatures of a LINER/Seyfert 2 type nuclear activity (Ho et al. 1997). With NGC 3623 and NGC 3628, it forms the well-known Leo Triplet (M 66 Group, VV 308). Since the discovery of a long plume extending about 50′ from the east of NGC 3628 (Zwicky 1956; Haynes et al. 1979), evidence of past interactions between NGC 3627 and NGC 3628 (the two largest spirals in the group), the Leo Triplet has been extensively studied from the radio to the optical, and in X-ray bandpasses. Optical broad-band images of NGC 3627 reveal a pronounced and asymmetric spiral pattern with heavy dust lanes, indicating strong density wave action (Ptak et al. 2006). While the western arm is accompanied by weak traces of star formation (SF) visible in \( H\alpha \), the eastern arm contains a star-forming segment in its inner part (Smith et al. 1994). NGC 3627 also possesses X-ray properties of a galaxy with a recent starburst (Dahlem et al. 1999). Both the radio continuum (2.8 cm and 20 cm) and the \( ^{12}\) CO(1−0) emissions show a nuclear peak, extend along the leading edges of the bar forming two broad maxima at the bar ends, and then the spiral arms trail off from the bar ends (Haan et al. 2008; Paladino et al. 2008; Haan et al. 2009). On the contrary, the \( H\alpha \) emission exhibits a spiral morphology without signatures of a bar in the atomic gas (Haan et al. 2008; Walter et al. 2008; Haan et al. 2009).

The most recent \( H\alpha \) mass determination for NGC 3627 has been obtained by Haan et al. 2008, \( M_{H\alpha} = 8.1 \times 10^8 M_\odot \) (reported to our adopted distance of \( D = 10.2 \) Mpc), on average less than the typical value expected for interacting galaxies of the same Hubble type (Casasola et al. 2004). The \( H\alpha \) mass con-

| Table 1. Fundamental parameters for NGC 3627. |
|---------------------|--------------------------|
| Parameter           | Value                     | Reference |
| \( \alpha_{2000} \)  | 1°20′00″.02″              | (1)       |
| \( \delta_{2000} \)  | 12°59′29″.50″             | (1)       |
| \( V_{hel} \)       | 744 km s\(^{-1}\)         | (1)       |
| RC3 Type            | SAB(s)b                  | (2)       |
| Nuclear Activity    | LINER/Seyfert 2           | (3)       |
| Inclination         | 61.3°                    | (1)       |
| Position Angle      | 178° ± 1°                | (1)       |
| Distance            | 10.2 Mpc (1″ = 49 pc)     | (2)       |
| \( L_B \)           | \( 4.2 \times 10^{10} L_\odot \) | (4)       |
| \( M_{H\alpha} \)   | \( 8.1 \times 10^8 M_\odot \) | (5)       |
| \( M_{IR} \)        | \( 4.1 \times 10^8 M_\odot \) | (6)       |
| \( M_{FIR}(60 \text{ and } 100 \mu m) \) | \( 4.5 \times 10^8 M_\odot \) | (4)       |
| \( L_{FIR} \)       | \( 1.2 \times 10^{10} L_\odot \) | (7)       |

\( \alpha_{2000}, \delta_{2000} \) is the position tracking center of our \(^{12}\) CO interferometric observations, assumed coincident with the dynamical center of NGC 3627 (see Sect. 4.1). Luminosity and mass values extracted from the literature have been scaled to the distance of \( D = 10.2 \) Mpc.

(1) This paper; (2) NASA/IPAC Extragalactic Database (NED, http://nedwww.ipac.caltech.edu/); (3) Ho et al. (1997); (4) Casasola et al. (2004); (5) Haan et al. (2008); (6) Kuno et al. (2007); (7) IRAS Catalog.
Table 2. $^{12}\text{CO}(1–0)$ flux values, both obtained by our observations and extracted from the literature, for NGC 3627.

| Reference         | Telescope   | Diameter [m] | Primary beam or FOV $^a$ | Beam $^b$ × $^c$ | Flux [Jy km s$^{-1}$] |
|-------------------|-------------|--------------|--------------------------|-----------------|----------------------|
| Young et al. (1995) | FCRAO       | 14           | 45                                      | 2.1 × 1.3       | 786                  |
| This paper        | PdBI+30 m   | 42           | 22 $^d$                                      | 2.0 × 1.3       | 251                  |
| This paper        | PdBI+30 m   | 22 $^d$                                      | 2.1 × 1.3       | 359                  |
| This paper        | PdBI        | 22 $^d$                                      |               |                     |
| This paper        | 30 m        | 30           | 22 (central position)                | 343$^e$         |
| Heister et al. (2003) | NRAO      | 12           | 55 (inner 50″×50″)                      | 1100–1200       |
| This paper        | 30 m        | 30           | 22 (inner 50″×50″)                      | 1097$^f$        |

$^a$ Primary beam is considered for single-dish observations, while field-of-view (FOV) for interferometric or combined (interferometric+single-dish) ones.

$^b$ The photometry has been performed within 22″, the $^{12}\text{CO}(1-0)$ primary beam for the 30 m telescope.

$^c$ The $^{12}\text{CO}(1-0)$ recovered flux for the central position (0°, 0″).

$^d$ The $^{12}\text{CO}(1-0)$ recovered flux for inner ~50″×50″, 5 × 5 mapping with 7″ spacing (see Sect. 2.2).

2. Observations

2.1. Interferometric observations

We observed NGC 3627 with the IRAM PdBI (6 antennas) in the ABCD configuration of the array between 2003 September and 2004 February in the $^{12}\text{CO}(1–0)$ [115 GHz] and the $^{12}\text{CO}(2–1)$ [230 GHz] line. The PdBI receiver characteristics, the observing procedures, and the image reconstruction are similar to those described in García-Burillo et al. (2003). The quasar 3C454.3 was used for bandpass calibration, 3C273 for flux calibration, and 1546+027 for phase and amplitude calibrations.

Data cubes with 512 × 512 pixels (0″.27 pixel$^{-1}$) for $^{12}\text{CO}(1–0)$ and 0″.13 pixel$^{-1}$ for $^{12}\text{CO}(2–1)$ were created over a velocity interval of -242.5 km s$^{-1}$ to +242.5 km s$^{-1}$ in bins of 5 km s$^{-1}$. The images presented here were reconstructed using the standard IRAM/GILDAS$^2$ software (Guilloteau & Lucas 2000) and restored with Gaussian beams of dimensions 2′′ × 1′′ (PA = 23°) at 115 GHz and 0′′.9 × 0′′.6 (PA = 28°) at 230 GHz. We used natural and uniform weightings to generate $^{12}\text{CO}(1–0)$ and $^{12}\text{CO}(2–1)$ maps, respectively. This allows to maximize the flux recovered in $^{12}\text{CO}(1–0)$ and optimize the spatial resolution in $^{12}\text{CO}(2–1)$. In the cleaned maps, the rms levels are 3.7 mJy beam$^{-1}$ and 6.7 mJy beam$^{-1}$ for the $^{12}\text{CO}(1–0)$ and $^{12}\text{CO}(2–1)$ lines, respectively, at a velocity resolution of 5 km s$^{-1}$. At a level of 3σ no 3 mm (1 mm) continuum was detected toward NGC 3627 down to an rms noise level of 0.34 mJy beam$^{-1}$ (0.48 mJy beam$^{-1}$). The conversion factors between intensity and brightness temperature are 34 K (Jy beam$^{-1}$) at 115 GHz and 41 K (Jy beam$^{-1}$) at 230 GHz. All velocities are referred to the systemic velocity $V_{sys,rel} = 744$ km s$^{-1}$ and $\langle \Delta \sigma, \Delta \phi \rangle$ offsets are relative to the phase tracking center of our observations (11′′, 15.02′′, 12′′, 59′′, 29.50′′). [see later Sect. 4.1] All maps are centered on

1 Paturel et al. (2003), http://leda.univ-lyon1.fr

2 http://www.iram.fr/IRAMFR/GILDAS/
Fig. 1. Spectra maps of NGC 3627 made with the IRAM 30 m with 7″ spacing in $^{12}$CO(1–0) [top] and $^{12}$CO(2–1) [bottom]. The positions are arcsec offsets relative to the phase tracking center of our interferometric observations (see Table 1). Each spectrum has a velocity scale from $-300$ to $300$ km s$^{-1}$, and a beam-averaged radiation temperature scale ($T_{mb}$) from $-0.10$ to $0.48$ K for $^{12}$CO(1–0) and from $-0.25$ to $0.70$ K for $^{12}$CO(2–1).

This position (see Table 1) and are not corrected for primary beam attenuation.

2.2. Single-dish observations

We performed IRAM 30 m telescope observations of NGC 3627 on July 16-19, 2002, in a $5 \times 5$ raster pattern with 7″ spacing. By using 4 SIS receivers, we simultaneously observed the frequencies of the $^{12}$CO(1–0) [115 GHz], the
12\(^\text{CO}(2–1)\) [230 GHz], and the HCN(1–0) [89 GHz] lines. The 12\(^\text{CO}(2–1)\) line has been observed in dual-polarization. The half power beam widths (HPBW) are 22\(^\prime\prime\), 12\(^\prime\prime\), and 29\(^\prime\prime\) for 12\(^\text{CO}(1–0)\), 12\(^\text{CO}(2–1)\), and HCN(1–0) lines, respectively. Typical system temperatures were ~110-145 K at 115 GHz, ~320-750 K at 230 GHz, and ~110-145 K at 89 GHz. For the single-dish data reduction, the Continuum and Line Analysis Single-dish Software (CLASS\(^2\)) was used. Throughout the paper we express the line intensity scale in units of the beam-averaged radiation temperature \((T_{\text{mb}})\). \(T_{\text{mb}}\) is related to the equivalent antenna temperature reported above the atmosphere \((T_A^*)\) by \(\eta = T_A^* / T_{\text{mb}}\), where \(\eta\) is the telescope main-beam efficiency. At 115 GHz \(\eta = 0.79\), at 230 GHz \(\eta = 0.54\), and at 89 GHz \(\eta = 0.82\). All observations were performed in “wobbler-switching” mode, with a minimum phase time for spectral line observations of 2 s and a maximum beam throw of 240\(^\prime\prime\). The pointing accuracy was ~3\(^\prime\prime\)\(^\text{rms}\). The single-dish maps presented in this paper are centered on the phase tracking center of our interferometric observations (see Table I).

### 2.3. Short spacing correction

An interferometer is limited by the minimum spacing of its antennas. Because two antennas cannot be placed closer than some minimum distance \((D_{\text{min}})\), signals on spatial scales larger than some size \((\alpha \lambda / D_{\text{min}})\) will be attenuated. This effect, called the “missing flux” problem, is resolved by using single-dish observations to compute short spacings and complete the interferometric measurements.

By combining 30 m and PdBI data, we found the best compromise between good angular resolution and complete restoration of the missing extended flux by varying the relative weights of 30 m and PdBI observations. The combined PdBI+30 m maps have angular resolutions of 2\(^\prime\)1 × 1\(^\prime\)3 at PA = 23\(^\circ\) for the 12\(^\text{CO}(1–0)\) and 0\(^\prime\)9 × 0\(^\prime\)6 at PA = 30\(^\circ\) for the 12\(^\text{CO}(2–1)\). In the combined maps, the \(rms\) uncertainty \(\sigma\) in 5 km s\(^{-1}\) width velocity channels is 3.6 mJy beam\(^{-1}\) and 6.5 mJy beam\(^{-1}\) for the 12\(^\text{CO}(1–0)\) and 12\(^\text{CO}(2–1)\) lines, respectively. For these maps, the conversion factors between intensity and brightness temperature are 32 K (Jy beam\(^{-1}\))\(^{-1}\) at 115 GHz and 41 K (Jy beam\(^{-1}\))\(^{-1}\) at 230 GHz. All interferometric figures presented in this paper are realized with short-spacing-corrected data.

Within 22\(^\prime\prime\), the 12\(^\text{CO}(1–0)\) HPBW for the 30 m telescope, the map including only PdBI observations recovers a flux \(S_{\text{CO}(1–0)} = 251\text{ Jy km s}^{-1}\), 70% of the total flux measured with the combined PdBI+30 m map, \(S_{\text{CO}(1–0)} = 359\text{ Jy km s}^{-1}\). Table II reports both 12\(^\text{CO}(1–0)\) flux values determined with our observations (single-dish, interferometric, and combined PdBI+30 m) and those present in literature. In this table, Col. (1) indicates the reference, Cols. (2) and (3) are the telescope (single-dish or interferometer) and the diameter of the single-dish telescope respectively, Col. (4) is the primary beam of the instrument or the diameter used for the performed photometry, Col. (5) is the beam in interferometric measurements, and Col. (6) gives the measured flux. Table II shows that 12\(^\text{CO}(1–0)\) fluxes we obtained with interferometric observations, single-dish, and combined measurements (PdBI+30 m) are in good mutual agreement with each other and with data present in literature. Our 30 m observations give a value \(S_{\text{CO}(1–0)} = 343\text{ Jy km s}^{-1}\) for the central position, consistent with flux value found with PdBI+30 m data within the 12\(^\text{CO}(1–0)\) 30 m–HPBW (22\(^\prime\prime\)). The whole region covered with 30 m observations (~50\(^\prime\prime×50\(^\prime\prime\)) gives a flux of 1097 Jy km s\(^{-1}\), in agreement with the BIMA SONG survey\(^3\) (NRAO 12 m) measurements (Helfer et al. 2003) see Fig. 50, ~1100–1200 Jy km s\(^{-1}\)). Moreover, within the 42\(^\prime\) primary beam field of the PdBI, we recovered ~85% of the flux detected by Young et al. (1995) for the central position with the FCRAO (786 Jy km s\(^{-1}\)). A good agreement considering the uncertainties in the amplitude calibration and the non-correction by the primary beam attenuation.

### 2.4. Other images of NGC 3627

We also acquired the large-scale 12\(^\text{CO}(1–0)\) emission image available thanks to the BIMA SONG survey performed with the 10-element BIMA millimeter interferometer (Welch et al. 1996) at Hat Creek, California. This image was first published by Ragan et al. (2001) and Helfer et al. (2003), and covers a field of 350\(^\prime\)×410\(^\prime\) centered on the galaxy) with a pixel size of 1\(^\prime\), and a beam of 6\(^\prime\).6×5.5\(^\prime\).

Several infrared (IR) images are included in our analysis: the \(\text{Spitzer-IRAC 3.6}\mu m\) image (to trace the stellar component), the \(\text{Spitzer-IRAC 8}\mu m\) image (to visualize the Polycyclic Aromatic Hydrocarbons [PAH] features), and the \(\text{Spitzer-MIPS 70 and 160}\mu m\) images (to study the dust emission and resolve the SF regions). These IR images are avail-

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\(^3\) Berkley-Illinois-Maryland Association Survey of Nearby Galaxies.
Fig. 3. Left panel: $^{12}$CO(1–0) integrated spectrum and gaussian fit (red) in the inner $\sim 2''$ of NGC 3627 for PdBI+30 m combined data. The gaussian fit shows that the heliocentric systematic velocity is redshifted by 16 km s$^{-1}$ with respect to the heliocentric velocity of the center (0 km s$^{-1}$). Right panel: Same for $^{12}$CO(2–1). The gaussian fit shows that the heliocentric systematic velocity is redshifted by 18 km s$^{-1}$.

Fig. 4. Left panel: $^{12}$CO(1–0) integrated intensity contours observed with the IRAM PdBI+30 m toward the center of NGC 3627. The white star marks the coordinates of the dynamical center of the galaxy coincident with our phase tracking center (see Table 1), with offsets in arcseconds. The map, derived with 2σ clipping, has not been corrected for primary beam attenuation. The rms noise level is $\sigma = 0.16$ Jy beam$^{-1}$ km s$^{-1}$ and contour levels run from 3σ to 33σ with 6σ spacing and from 39σ to the maximum with 18σ spacing. In this map the ±200 km s$^{-1}$ velocity range is used. The beam of 2.1′′ × 1.3′′ is plotted in the lower left. Right panel: Same for $^{12}$CO(2–1). The rms noise level is $\sigma = 0.30$ Jy beam$^{-1}$ km s$^{-1}$ and contour levels run from 3σ to 39σ with 6σ spacing and from 45σ to the maximum with 18σ spacing. The beam of 0.9′′ × 0.6′′ is plotted at lower left.

We also use two near-infrared (NIR) images $H$ (1.65 μm): the first was taken from the Two Micron All Sky Survey (2MASS) and covers a FOV of $\sim 12'\times12'$, with a resolution of 2.5′. The second 1.6 μm $H$-band image of NGC 3627 is available thanks to the F160W filter on the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS, camera 3 [NIC3]) on board the Hubble Space Telescope (HST). This image cov-
ers a FOV of 51′′×51′′, has a resolution of 0′′.2, and is not exactly centered on the galaxy but offset from our phase tracking center 7′′ toward west and 7′′4 toward south. It is part of a survey of 94 nearby galaxies from the Revised Shapley Ames Catalog (Böker et al. 1999).

Finally, we also use a far-ultraviolet (FUV) image from the GALEX satellite, whose band is centered at λeff = 1516 Å. This image has been already used and studied in the context of the GALEX Nearby Galaxies Survey (NGS, Gil de Paz et al. 2007). The image covers a square region on the sky of size ∼5760′′×5760′′, i.e., much larger than the extent of the optical disk of NGC 3627, with 1′′5 pixels. As the image was reduced with the GALEX data pipeline, it is already expressed in intensity units and skysubtracted. The total FUV calibrated magnitude is 16.34±0.02, corresponding to a FUV flux density of 1057 μJy.

3. Single-dish results

The observations performed with the A and B receivers of the IRAM 30 m telescope in the two 12CO lines covered the inner ∼50′′, corresponding to the central ∼2.5 kpc (in diameter) of the galaxy (Fig. 1). The observed positions show that the central region of NGC 3627 hosts extended molecular emission both in 12CO(1–0) and 12CO(2–1). The maximum detected T_{mb} is 0.4 K in 12CO(1–0) at the offset position (0′′, -7′′), and 0.6 K in 12CO(2–1) at the offset position (0′′, 7′′).

We estimate a flux of 1097 Jy km s^{-1} within the inner ∼50′′×50′′ (see Table 2 and Sect. 2.3, in good agreement with previous single-dish flux determinations (e.g., Helfer et al. 2003). Assuming a H2-CO conversion factor of X = N(H2)/I_{CO} = 2.2 × 10^{20} cm^{-2} (K km s^{-1})^{-1} (Solomon & Barrett 1991), the 12CO(1–0) integrated flux allows us to derive the H2 mass within the observed region as:

\[ M_{H2}[\text{M}_\odot] = 8.653 \times 10^3 D^2 \text{[Mpc]} S_{CO(1-0)}/[\text{Jy km s}^{-1}] \] (1)

We derive an H2 mass of M_{H2}∼9.9×10^7 M_\odot within the inner ∼50′′×50′′, and taking into account the mass of helium, the total molecular mass is M_{mol} = M_{H2}+M_{He} = 1.36 × M_{H2}∼1.3×10^8 M_\odot.

The HCN(1–0) line has been observed for inner 25 positions with 7′′ spacing, covering the central ∼56′′ (∼2.7 kpc in diameter). The HCN(1–0) average spectrum over the 5×5 grid is displayed in Fig. 2 and shows a peak at T_{mb}∼0.009 K. The HCN(1–0) velocity integrated intensity of the central position (0′′, 0′′) is I_{HCN(1-0)} = 3.1±0.3 K km s^{-1} with Δv = 237±32 km s^{-1}, consistent with the results obtained by Krips et al. (2008) for the same position observed with the same instrument (I_{HCN(1-0)} = 2.7±0.2 K km s^{-1} with Δv = 290±30 km s^{-1}). The CO(1–0)/HCN(1–0) ratio averaged on the center of galaxy is roughly 10, a value intermediate between the ratios found in spatially resolved molecular disks around AGN, such as NGC 6951 (Krips et al. 2007) and NGC 1068 (Krips et al. 2008), and those found in pure starburst galaxies such as M 82 (Krips et al. 2008).

4. Interferometric results

4.1. Dynamical center

The phase tracking center of our observations (see Table 1) coincides almost exactly with the nuclear radio source detected at 15 GHz (VLA/2 cm) by Nagar et al. (2000) [11^h20^m15.01^s, 12^h59′29″.76] and at 8.4 GHz (VLA/3.6 cm) by Filho et al. (2001) [11^h20^m15.0′, 12^h59′30″]. Thus, in the following, we assume that our observations are centered on the dynamical center of NGC 3627.

The spectral correlators were centered at 114.992 GHz for 12CO(1–0) and 229.979 GHz for 12CO(2–1), corresponding to V_{LSR} = 727 km s^{-1}. Since for NGC 3627 the difference between LSR and heliocentric velocity is ∼0 km s^{-1}, our observations were centered on V_{LSR} = V_{hel}(PdBI) = 727 km s^{-1}. In the inner ∼2′′ of NGC 3627 the velocity centroid is 16 km s^{-1} redshifted with respect to the heliocentric velocity of the center of our 12CO(1–0) observations (Fig. 3 left panel). Similarly to 12CO(1–0), for 12CO(2–1) we find that the velocity centroid is 18 km s^{-1} redshifted with respect to the heliocentric velocity (Fig. 3 right panel). Assuming an intermediate value between the systemic heliocentric velocity determined for the 12CO(1–0) and that for the 12CO(2–1), we estimate V_{sys,hel} = 744 km s^{-1}.

This estimation of the systemic heliocentric velocity is 24 km s^{-1} redshifted with respect to the systemic heliocentric velocity determined from Hα observations (720 km s^{-1}, HyperLeda Database; Haan et al. 2008). In interacting galaxies and in those with a lopsided Hα morphology, a discrepancy between systemic velocity derived from 12CO and Hα observations is not unusual. NGC 4579 (García-Burillo et al. 2009) and NGC 5953 (Casasola et al. 2010) exhibit differences of ∼50 km s^{-1} between 12CO and Hα velocities, perhaps due to the interaction history of the galaxy and the different effect of the ram
pressure on the atomic and molecular gas (García-Burillo et al. 2009). In NGC 3627, the role of interaction history and the ram-pressure, although not negligible, could have shifted the H I barycenter with respect to the molecular one less strongly than in NGC 4579 and NGC 5953.

4.2. CO distribution and mass

Figure 6 shows the $^{12}$CO(1–0) and $^{13}$CO(2–1) integrated intensity distributions in the inner $\sim$40$''$ (~2 kpc) of NGC 3627. The $^{12}$CO(1–0) emission (Fig. 6, left panel) exhibits a peak at the nucleus, extends along a bar-like structure of $\sim$18$''$ (~900 pc) diameter with a north/south orientation (see later Sect. 4.4 for the discussion on the PA) and two peaks at its extremes, at $r \sim$5-6$''$ (~270 pc), with the southern one more evident. The
Fig. 7. Same as Fig. 6 but for the $^{12}$CO(2–1) line, with a spatial resolution of $0''9 \times 0'6$. The contours run from $-50\text{ mJy beam}^{-1}$ to $350\text{ mJy beam}^{-1}$ with spacings of $50\text{ mJy beam}^{-1}$.

$^{12}$CO(1–0) morphology also shows a two-arm spiral feature from $r\sim 9''$ ($\sim 450$ pc) to $r\sim 16''$ ($\sim 800$ pc), with two peaks over these spiral arms at $r\sim 12-14''$ ($\sim 650$ pc). A similar and more resolved distribution is found in $^{12}$CO(2–1) [Fig. 4, right panel]. Like the nuclear peak, the two peaks at the ends of the inner $\sim 18''$ bar-like structure at $r\sim 5-6''$, are more evident than in $^{12}$CO(1–0).

The $^{12}$CO distribution found here agrees well with previous molecular gas maps, such as that given by Regan et al. (2001) and Helfer et al. (2003) in the context of the BIMA SONG survey and that obtained by Kuno et al. (2007) with the 45 m telescope of the Nobeyama Radio Observatory. Although we only observed the inner $\sim 2$ kpc of the galaxy, the good PdBI resolution allows us to investigate the nuclear molecular gas distribution in NGC 3627 more in detail than in BIMA SONG survey (typical resolution of $\sim 6''$) and with the 45 m NRAO telescope (FWHM $\sim 15''$). The $^{12}$CO distribution is completely different from the ringed HI morphology which exhibits an inner hole where instead the molecular gas is located (Haan et al. 2008; Walter et al. 2008).

Applying Eq. (1) to combined PdBI+30 m data, we derived a total H$_2$ mass of $M_{\text{H}_2} \sim 6.0 \times 10^8$ M$_\odot$ ($S_{\text{CO}} = 668$ Jy km s$^{-1}$, see Table 2) within the 42'' primary beam field of the PdBI. Taking into account the mass of helium, the total molecular mass is
Fig. 8. Left panel: Overlay of the integrated $^{12}$CO(1–0) emission, same as Fig. 4 (left panel), with CO mean-velocity field in contours spanning the range -180 to 180 km s$^{-1}$ in steps of 10 km s$^{-1}$. The white star indicates the dynamical center of the galaxy. The velocities are referred to $V_{\text{sys, hel}} = 744$ km s$^{-1}$, solid (red) lines are used for positive velocities, and dashed (blue) lines for negative velocities. The dashed line indicates the position angle of the major axis of the whole observed region ($PA = 178^\circ \pm 1^\circ$), while the dot-dashed line traces the position angle of the major axis of the bar-like structure ($PA = 14^\circ \pm 2^\circ$). The continuum line indicates the position angle of the primary stellar bar identified with the NIR H-band 2MASS image ($PA = -21^\circ$) [see later the left panel of Fig. 16 and Sect. 5.2]. Right panel: Same for $^{12}$CO(2–1). The dashed line indicates the position angle of the major axis of the whole $^{12}$CO(1–0) observed region ($PA = 178^\circ \pm 1^\circ$, see left panel), while the dot-dashed line traces the position angle of the major axis of the $^{12}$CO(2–1) bar-like structure ($PA = 15^\circ \pm 2^\circ$). The continuum line indicates the position angle of the primary stellar bar identified with the NIR H-band 2MASS image ($PA = -21^\circ$) [see later Fig. 16 and Sect. 5.2].

M$_{\text{mol}}$×8.2×10$^8$M$_\odot$. This is roughly 63% of the molecular gas mass within a 50″ diameter (see Sect. 3). The $\sim 18''$ $^{12}$CO(1–0) bar-like structure contributes an H$_2$ mass of M$_{\text{H}_2}$×2.1×10$^8$ M$_\odot$, roughly one-third of the H$_2$ mass computed within 42″, although the feature occupies an area of only ~5% of the 42″ beam. NGC 3627, compared to other NUGA galaxies, is not particularly massive in molecular gas, especially with respect to the extraordinary case of NGC 1961 with an H$_2$ mass of $\sim 1.8×10^{10}$ M$_\odot$. (Combes et al. 2009).

4.3. CO(2–1)/CO(1–0) line ratio

Information about the local excitation conditions of the molecular gas can be inferred from the line ratio $R_{21} = I_{21}/I_{10}$. This ratio is obtained by comparing the $^{12}$CO maps of the two transitions, at the same resolution and with the same spatial frequency sampling. Figure 5 shows $R_{21}$ ratio with $^{12}$CO(1–0) contours as in Fig. 4 (left panel). In the observed region, the line ratio ranges from 0.25 to 1 but the bulk of the emission has a ratio between 0.4 and 0.7. These $R_{21}$ line ratio values are consistent with $R_{21} = 0.6$ obtained by Krips et al. (2008), and more in general with optically thick emission in spiral disks (e.g., Braine & Combes 1992, García-Burillo et al. 1993). The $R_{21}$ peaks of ~1 are reached in the center of NGC 3627 and at the southern extreme of the elongated $^{12}$CO emission region. A higher excitation of the molecular gas in the nucleus, suggested by a higher $R_{21}$ line ratio, is consistent with the HCN(1–0) emission in the same region (see Sect. 5).

4.4. CO Kinematics

Figures 6 and 7 show the velocity-channel maps of $^{12}$CO(1–0) and $^{12}$CO(2–1) emission, respectively, in the central region of NGC 3627. The inner $^{12}$CO emission of the galaxy exhibits signatures of non-circular motions both at negative and positive velocities. These non-circular components are associated both with the 18″ bar-like structure and the spiral feature detected beyond the bar-like structure and will be discussed in detail later, in Sect. 4.5, where we analyze the rotation curve derived with our $^{12}$CO data.

$^{12}$CO(1–0) isovelocity contours (first-moment map) are superposed on the $^{12}$CO(1–0) integrated intensity in Figure 8 (left panel). The white star indicates the dynamical center of the galaxy, assumed coincident with the phase tracking center of our observations, and the velocities are relative to the systemic heliocentric velocity, $V_{\text{sys, hel}} = 744$ km s$^{-1}$ (see Sect. 4.1). The dashed line traces the position angle of the major axis of the observed region, $PA = 178^\circ \pm 1^\circ$ (almost vertical), obtained by maximizing the symmetry in the position velocity diagrams. This position angle is close to that of the entire galaxy, as given
Fig. 9. Left panel: $^{12}$CO(1–0) position-velocity diagram along the major axis (PA = 178°) of NGC 3627 using the velocity range from -220 to 220 km s$^{-1}$ contoured over a grey-scale representation. Contour levels are from 3σ to 48σ in steps of 3σ ($σ$=3.6 mJy beam$^{-1}$). The velocities are relative to $V_{\text{sys, hel}}$ (= 744 km s$^{-1}$) and X are the offsets along the major axis in arcsecs. Right panel: The same for $^{12}$CO(2–1). Contour levels are from 3σ to 30σ in steps of 3σ ($σ$=6.7 mJy beam$^{-1}$).

Fig. 10. Left panel: Same as Fig. 9 along the minor axis (PA = 88°) of NGC 3627. Contour levels are from 3σ to 57σ in steps of 3σ ($σ$=3.6 mJy beam$^{-1}$). Y are the offsets along the minor axis in arcsecs. Right panel: The same for $^{12}$CO(2–1). Contour levels are from 3σ to 35σ in steps of 3σ ($σ$=6.7 mJy beam$^{-1}$).

by the surface brightness profiles (172°, see Sect. 5.2), and given in the Uppsala General Catalog (173°). The dot-dashed line traces the position angle of the major axis of the bar-like structure, PA = 14° ± 2°. The right panel of Fig. 8 shows $^{12}$CO(2–1) isovelocity contours on the $^{12}$CO(2–1) integrated intensity, where the position angle of the major axis of the observed region is very similar to that found for the $^{12}$CO(1–0) inner region (PA = 15° ± 2°). The continuous lines, in the left and right panels of Fig. 8 show the PA of the stellar bar identified in the NIR with the $H$-band 2MASS image (PA = −21°) [see below the left panel of Fig. 16 and Sect. 5.2]. The different PAs of the stellar bar and the molecular gas bar-like structure suggest that the gas is leading the stellar bar. Signatures of non-circular motions are visible also in Fig. 8 since the isovelocity contours appear severely tilted along the molecular gas bar-like structure both in $^{12}$CO(1–0) and $^{12}$CO(2–1).
Fig. 11. Left panel: The $^{12}$CO(1–0) RC derived as described in the text. The positive (negative) velocities, corrected for inclination, are shown as a red dashed (blue dotted) line; the black line shows the average. The horizontal dot-dashed line at 180 km s$^{-1}$ indicates the velocity of the bulk of the molecular gas. Right panel: The same as the left panel, but for $^{12}$CO(2–1).

Figures 9 and 10 show position-velocity (p-v) cuts along the major (PA = 178°) and minor axis (PA = 88°) of NGC 3627, respectively. In both figures, the $^{12}$CO(1–0) emission is given in the left panel and $^{12}$CO(2–1) in the right. Our p-v plots along major axis are consistent with the $^{12}$CO(1–0) p-v diagram obtained by Regan et al. (2002), where the different velocity range between nuclear region and bar ends is yet clearer, because they mapped in $^{12}$CO(1–0) the whole galaxy. Regan et al. (2002)’s p-v diagram (Fig. 5a in their paper) shows that the components we found at 10–15′′ (not corrected for inclination) maintain this velocity also at larger radii (until ~50′′ from the center), and then again increase and reach the velocity assumed by bar ends.

4.5. CO rotation curve and dynamical mass

We have derived a rotation curve (RC) from the p-v diagram along the kinematic major axis of NGC 3627 (PA = 178°). By fitting multiple gaussian profiles to the spectra across the major axis we calculated the terminal velocities, and the fitted velocity centroids, corrected for inclination ($\sin i$, $i =$61°3′), give $V_{\text{obs}}/\sin i$ for each galactocentric distance. Figure 11 shows RCs for $^{12}$CO(1–0) [left] $^{12}$CO(2–1) [right], where for each line we plotted both the two curves derived from either side of the major axis and their combination into a average by spline interpolation. This interpolation is justified by the similar behavior of the positive velocity curve and the negative velocities for both lines.

The $^{12}$CO(1–0) RC reaches a maximum of 180 km s$^{-1}$ (velocity corrected for inclination) at r = 4′′3 (~0.2 kpc), and then decreases until velocities between ~60 km s$^{-1}$ and ~85 km s$^{-1}$ maintaining these velocities until ~15′′ (~0.74 kpc) from the center (Fig. 11 left panel). The $^{12}$CO(2–1) RC shows a similar maximum velocity, ~183 km s$^{-1}$, reached at r < 5′′ (Fig. 11 right panel). At larger distances from the nucleus (r > 15′′), we expect that the RC again increases until ~180 km s$^{-1}$, the velocity at the ends of the bar, consistently with p-v plots mapping the whole galaxy (e.g., Regan et al. 2002). Asymmetries are also seen in the Hα RC of NGC 3627 (Chemin et al. 2003), both in the inner disk (between 25′′ and 34′′ from the nucleus, already outside the range of our $^{12}$CO observations) and at larger radii (>88′′). The form of the RC of NGC 3627, with remarkable dips in velocity near the nucleus, is not unusual for galaxies with circumnuclear bars or gas disks (e.g., Rubin et al. 1997).

Such behavior often reflects non-circular motions depending both on the internal structure of the galaxy (e.g., the bar and consequent streaming motions) and the orbital parameters of the interaction with nearby companions. Another important source of non-circular motions may be the kinematic feedback to the gas from star formation (Beauvais & Bothun 1999). Regions of intense SF and turbulent motions in those regions may lead to an increase in the local velocity dispersion. In NGC 3627, the dips may be due to all three mechanisms, a combination of the effects of the interaction, the strong bar, and the kinematic feedback to the gas from SF.

From the RC, we can estimate the dynamical mass within a certain radius with the formula $M(R) = 2.325 \times 10^{5} \alpha RV^{2}(R)$ where $M(R)$ is in $M_{\odot}$, $R$ in kpc, $V$ in km s$^{-1}$, and $\alpha$ is a factor related to the geometry. The choice of $V$ to use in the above formula is complicated by the presence of dips in the RC (Fig. 11). Although these dips are due to non-circular motions, at larger radii both CO (e.g., Regan et al. 2002) and H$\alpha$ (e.g., Zhang et al. 1999; Haan et al. 2008) RCs are flat and at the same velocity found at the bar ends. We can thus estimate the dynamical mass using the maximum velocity of 180 km s$^{-1}$ (corrected for inclination) reached at ~210 pc from the center.

Assuming for $\alpha$ a value of 0.8, intermediate between the value appropriate for a spherical distribution (1.0) and that for a flat disk (0.6), the above formula gives a dynamical mass of $M_{\text{dyn}} = 1.3 \times 10^{9} M_{\odot}$ within a radius of 4′′3 (~0.2 kpc). Continuing to neglect non-circular motions and assuming a roughly flat RC also at larger radii, the dynamical mass should be $M_{\text{dyn}} = 6.0 \times 10^{9} M_{\odot}$ within a radius of 21′′ (~1 kpc). In the same region, we estimate a H$_2$ mass of $6.0 \times 10^{9} M_{\odot}$ (see
Sect. 4.2, ~10% of the dynamical mass. Zhang et al. (1993) found a dynamical mass of $M_{\text{dyn}} = 5.8 \times 10^9 M_\odot$ (value scaled to our adopted distance of $D = 10.2 \text{ Mpc}$) within a radius of $23''$, a value consistent with our determination in a similar region, considering uncertainties from a different assumed inclination and rotation velocity. Moreover, Zhang et al. (1993) found a ratio $M_{\text{HI}}/M_{\text{dyn}} \sim 11\%$ within the radius of $23''$, similar to our value. Nevertheless, because of the clear signature of non-circular motions in the RC, our estimate of dynamical mass is very uncertain, probably ±50%.

5. Comparison with other data

Here we present a comparison of our $^{12}\text{CO}$ observations and images at other wavelengths available for NGC 3627. These comparisons allow both to assess possible correlations between different tracers of the ISM and to determine the location of the dynamical resonances, useful for probing gas inflow in the circumnuclear region of the galaxy. All images have been centered on the phase tracking center of our $^{12}\text{CO}$ interferometric observations (see Table 1), and -when necessary- properly rotated with North up and E left.

5.1. Another $^{12}\text{CO}$ map: NUGA vs. BIMA SONG

The left panel of Figure 12 shows the BIMA SONG $^{12}\text{CO}(1-0)$ emission image of NGC 3627 (Regan et al. 2001). The beam of 6′′ × 5′′ is plotted in the lower left. The inner 320′′ are shown. Right panel: NUGA $^{12}\text{CO}(1-0)$ contours (in white) as in Fig. 4 (left panel) overlaid on the BIMA SONG $^{12}\text{CO}(1-0)$ emission image. The $^{12}\text{CO}(1-0)$ NUGA beam of 2′′1 × 1′′3 is plotted in the lower left. The inner 40′′ are shown.

The two $^{12}\text{CO}$ data sets agree quite well; the only significant disagreement is present toward the south, where our higher-resolution $^{12}\text{CO}(1-0)$ contours delineate a barred structure that develops mainly toward the south, while the BIMA SONG $^{12}\text{CO}(1-0)$ emission is more rotated toward the east/south-east.

5.2. Near- and mid-infrared emission

NIR images of NGC 3627 have been used both to derive the surface brightness profiles and to perform comparisons with our $^{12}\text{CO}$ observations. We compared the surface brightness profiles of the ground- and space-based images by extracting elliptically averaged profiles, centered on the brightness peaks. The position angle and ellipticity were allowed to vary in the ellipse fitting. These radial profiles are shown in Figure 13, where the dashed horizontal lines in the lower panels correspond to the adopted position angle (PA) and inclination ($i$). The three profiles ($HST$ F160W represented by the solid (blue) line, IRAC 3.6 $\mu$m by the dotted (green) line, and IRAC 8 $\mu$m by the dashed (red) line) are quite similar, in particular the $HST$ F160W and the IRAC 3.6 $\mu$m images show a similar trend within the inner 10′′. Also shown are the runs of ellipticity $\varepsilon$, ellipse position angle $\theta$, and $\cos(4\theta)$ residuals of the ellipse fitting. The adopted PA is 178° (see Sect. 4.4), similar to the fitted PA of 172°. The inclination computed from the elliptical fits of the IRAC 3.6 $\mu$m image converges to 61.3°, very close to the inclination given by NED, 62.5°.

Figure 14 shows a large-scale view of NGC 3627 at 8 $\mu$m (Spitzer-IRAC). The longest-wavelength 8 $\mu$m IRAC band is
Fig. 13. The upper panels show radial surface brightness profiles of NGC 3627 made by fitting elliptical isophotes. The left panel shows a smaller FOV than the right panel. The solid (blue) line corresponds to HST F160W, the dotted (green) line to IRAC 3.6 μm, and the dashed (red) line to IRAC 8 μm. The lower panels display the radial runs of ellipticity \( \epsilon \), position angle \( \theta \), and \( \cos(4\theta) \) terms in the ellipse fitting residuals. The adopted PA (178°, see Sect. 4.4) and the best-fit inclination (61.3°) are shown by dashed horizontal lines in the lower panels. The dashed vertical line shows a radius of 1 kpc (20′′).

Fig. 14. The large-scale IRAC 8 μm image of NGC 3627 centered on the phase tracking center of our \( ^{12}\text{CO} \) interferometric observations. The inner 330′′ are shown. The emission is dominated by PAHs and perhaps some hot dust continuum emission. This figure clearly reveals a spiral pattern, asymmetric with respect to the major axis, and heavy dust lanes, signature of a strong density wave action. This image also shows an evident perturbed morphology of the eastern arm. The bulk of the inner warm dust emission appears configured in a smooth elongated (north/south) disk, but the large-scale bar seen in the BIMA-SONG CO image is clearly reflected in the 8 μm emission.

Figure 15 shows the stellar morphology traced by the 3.6 μm (Spitzer-IRAC) emission in the circumnuclear region of NGC 3627, with overlaid \( ^{12}\text{CO}(1–0) \) [left panel] and \( ^{12}\text{CO}(2–1) \) [right panel] intensity contours. This comparison shows that the large-scale 3.6 μm stellar bar and the molecular gas bar-like feature have different orientation in the plane of the galaxy. The stellar bar has a PA of \(-21°\), while the molecular bar has a PA of \(-14°\) in \( ^{12}\text{CO}(1–0) \) and \(-15°\) in \( ^{12}\text{CO}(2–1) \) [see Sect. 4.4]. This difference in orientation suggests that the molecular gas is leading the stellar bar. The right panel of Fig. 13 shows clear signatures of a bar-like feature at 3.6 μm at a radius of 60-70′′: the surface brightness undergoes an inflection; the ellipticity dips; and the PA changes slightly. The bar would thus have a radius between 3 and 3.4 kpc.

The 1.6 μm (H-band, 2MASS) large-scale morphology of NGC 3627 is shown in the left panel of Figure 16. Most of the stellar mass in a typical galaxy is locked up in cool stars, whose light is emitted longward of 1 μm. Since the stellar spec-
Fig. 15. Left panel: $^{12}$CO(1–0) integrated intensity contours as in Fig. 4 (left panel) overlaid on the IRAC 3.6 $\mu$m image of NGC 3627 in false color. The inner 40$''$ are shown. Right panel: Same for $^{12}$CO(2–1) integrated intensity contours as in Fig. 4 (right panel). The inner 20$''$ are shown.

Fig. 16. Left panel: Large-scale H-band 2MASS image of NGC 3627 centered on the phase tracking center of our $^{12}$CO interferometric observations. The inner 330$''$ are shown. Right panel: Inner 9$''$ of the F160W/HST H-band image of NGC 3627 rotated with N up and E left and centered on the phase tracking center of our $^{12}$CO interferometric observations with overlaid NUGA $^{12}$CO(2–1) contours (in green) as in Fig. 4 (right panel).

The spectrum tends to peak around 1.6 $\mu$m, corresponding to the H-band NIR window. 1.6 $\mu$m emission is an effective tracer of stellar mass. Like the emission at 3.6 $\mu$m, the 1.6 $\mu$m morphology of NGC 3627 is much smoother than that found at 8 $\mu$m (Fig. 14), the former maps trace the older stellar population, while the latter is tracing the sites of star formation which tend to be clumpy, with a more inhomogeneous distribution. Like the 3.6 $\mu$m emission, the H-band image shows a large-scale stellar bar with PA = −21° and a radius of roughly 3-3.4 kpc (60-70$''$).

Another H-band image of NGC 3627 is available thanks to the F160W filter on the HST/NIC3 camera, described in Sect. 2.4. Although the smaller FOV of the NIC3 camera (51$''$×51$''$), the superior spatial resolution of the F160W/HST H-band image (0$''$.2), compared with that of the H-band 2MASS im-
Fig. 17. **Left panel:** Large-scale Spitzer-MIPS 70 µm image of NGC 3627, centered on the phase tracking center of our 12CO interferometric observations. The inner 420″ are shown. The (red) box shows the central 200″, displayed in the **right panel.** **Right panel:** BIMA 12CO(1–0) integrated intensity contours overlaid on the Spitzer-MIPS 70 µm image of NGC 3627. The inner 200″ are shown.

Fig. 18. **Left panel:** Large-scale Spitzer-MIPS 160 µm image of NGC 3627, centered on the phase tracking center of our 12CO interferometric observations. The inner 420″ are shown. The (red) box shows the central 200″, displayed in the **right panel.** **Right panel:** BIMA 12CO(1–0) integrated intensity contours overlaid on the Spitzer-MIPS 160 µm image of NGC 3627. The inner 200″ are shown.

The 12CO(1–0) emission is more elongated relative to the 1.6 µm (F160W/HST) one, the sizes of the two inner (~3″) distributions are similar and the two central peaks coincide. The central emission at 1.6 µm is distributed in a disk, with a central peak and a depression toward the NE caused by dust extinction. The dust feature gives...
a clue about the orientation of the galactic disk. Because dust on the near side of the galaxy obscures what is behind it, we can deduce that the eastern side is closer than the western side. Such an orientation would be consistent with the blue-shifted velocities toward the north (see Fig. 8), and the expectation that the spiral arms should be trailing.

5.3. Far-infrared emission

Most of the dust mass in galaxies is relatively cool, radiating primarily at wavelengths of the Spitzer-MIPS 70 and 160 $\mu$m bands. The left panels of Figures 17 and 18 which display the inner 420$''$ of the Spitzer-MIPS 70 and 160$\mu$m images of NGC 3627, respectively, show that the dust emission is intensified at the nucleus and at the ansae at the ends of the bar. The right panels of these figures display the BIMA $^{12}$CO(1–0) integrated intensity contours overlaid on the Spitzer-MIPS 70$\mu$m image (Fig. 17) and the Spitzer-MIPS 160$\mu$m image (Fig. 18) for the inner 200$''$ of NGC 3627. These comparisons show a very good correlation between the dust emission peaks and the $^{12}$CO emission along the bar. These regions with strong dust and $^{12}$CO emission could be the “highly obscured star-forming regions” identified by Prescott et al. (2007) by comparing 24$\mu$m and H$\alpha$ maps. This dust-CO correlation is particularly important in terms of SF, discussed below in Sect. 5.5.

5.4. Far-ultraviolet morphology

The left panel of Figure 19 shows the FUV image of NGC 3627 obtained with the GALEX satellite, described in Sect. 2.4. It can be seen that NGC 3627 has an asymmetric spiral structure in the FUV outside the range of our $^{12}$CO observations, as seen at other wavelengths (IR, but also $^{12}$CO from BIMA SONG survey). There is an inner elongated (north/south) ring delimiting a “hole”, or rather a net depression in the FUV emission around the nucleus. Along the edge of this ring, the FUV emission is not homogeneously distributed, but its north/northeastern arc exhibits FUV emission in the form of several clumps stronger than the rest of the ring. In the FUV, the eastern spiral arm, less extended, appears more luminous than the western one, while in the IR (8 $\mu$m [Fig. 14] and 1.6 $\mu$m [Fig. 16]) the two spiral arms are equally intense. The implication is that dust is suppressing the emission of the western arm. A similar ring is visible also in H$\alpha$ (Haan et al. 2008, 2009), larger than in the FUV GALEX emission but with the same elongated (north/south) morphology. The right panel of Fig. 19 shows our $^{12}$CO(1–0) contours as in Fig. 4 (left panel) superimposed on the FUV GALEX image for the inner 80$''$ of NGC 3627. The $^{12}$CO bar-like structure is contained in the inner hole observed in the FUV, indicating an anti-correlation between $^{12}$CO and FUV. The same anti-correlation is observable by comparing the FUV GALEX image with BIMA $^{12}$CO(1–0) contours, as displayed in Figure 20. Although the large scale views of the galaxy in FUV and $^{12}$CO(1–0) are similar (as demonstrated by the extension of the arms, especially the western one), in Fig. 20 we can appreciate some offsets between the two emissions. Shifts between molecular gas and FUV peaks are present along both spiral arms, and the strongest FUV peak, along the ring in the north/northeast direction, has no counterpart in molecular gas emission.
5.5. Star formation in NGC 3627

The FIR luminosity is often used as a measure of the current star formation rate (SFR), since it is assumed that FIR emission is mainly due to dust heating by massive young stars. The total IR luminosity of NGC 3627 is $1.3 \times 10^{44}$ erg s$^{-1}$, according to the precepts of Draine & Li (2007) and with fluxes from Dale et al. (2005). This corresponds to a SFR of $\sim 6 M_\odot$ yr$^{-1}$ (Kennicutt 1998). In the bulge of NGC 3627, there is little observed SF (Smith et al. 1994, Regan et al. 2002), and the SFR given by H$\alpha$ within a nuclear region of diameter $\sim 16''$ is $0.078 M_\odot$ yr$^{-1}$ (Regan et al. 2002), $\sim 3$ times lower than found in the bar itself, and $\sim 4$ times lower than the spiral arms (Regan et al. 2002). Part of this deficit in the nuclear H$\alpha$-derived SFR may arise from dust extinction, given that the mean $A_V$ in the inner 50'' (diameter) is $\sim 2$ mag (Calzetti et al. 2007). In any case, in NGC 3627, most of the SF is extranuclear, along the bar, particularly where it terminates and the spiral arms emerge (see Figs. 17 and 18).

The 70 $\mu$m emission is confined mainly to the nucleus and the bar, particularly the ansae (see Fig. 17). The 160 $\mu$m emission (albeit with lower resolution), is more broadly distributed, especially around the bar. This IR morphology suggests that the dust along the bar is warmer than around the bar, probably heated by the massive stars in the recent star-formation episodes.

In galaxies with weak SF activity (e.g. NGC 4736, Smith et al. 1994), dust heating by non-OB stars may also contribute significantly (e.g., de Jong et al. 1984, Bothun et al. 1989). This more quiescent heating source may be especially important in the central regions of early-type spiral galaxies with massive bulges and little nuclear or circumnuclear SF, such as NGC 3627. The ratio of FIR to H$\alpha$ luminosity for the bulge of NGC 3627 is of $\sim 8100$, significantly larger than for the star-forming regions in this galaxy, between $\sim 1000$ and $\sim 2000$. The $L$(FIR)/$L$(H$\alpha$) ratio is also higher than can be accounted for by obscured SF with a normal initial mass function, using extinction measurements derived from $^{12}$CO(1–0) and FIR data (Smith et al. 1994). Thus, the older stars probably contribute significantly to the dust heating in the bulge of NGC 3627 (Smith et al. 1994).

A low nuclear SFR is consistent with the CO/HCN ratio (10) discussed in Sect. 5. Higher ratios suggest that excitation by SF is dominant over AGN excitation in the circumnuclear region, but we found a “normal” CO/HCN ratio for NGC 3627, not surprisingly given its low SFR.

6. Computation of the torques on the molecular gas

The gravitational torques derived from the stellar potential in the inner region of NGC 3627 allow to account for the gas kinematics derived from CO and examine the efficiency of gravitational torques exerted on the gas. As described in previous NUGA papers (e.g. García-Burillo et al. 2005), to compute the gravitational torques we assume that NIR images give the best approximation for the total stellar mass distribution, being less
affected than optical images by dust extinction or stellar population bias.

6.1. Evaluation of the gravitational potential

We computed the torques using both HST-NICMOS F160W and Spitzer-IRAC 3.6 μm images. They yield complementary results, the torques computed from the HST-NICMOS F160W image compared with the 12CO PdBI contours allow to investigate the nuclear region of NGC 3627, while the torques derived from the Spitzer-IRAC image in combination with the 12CO BIMA contours are much better adapted to visualize the whole spiral structure of the galaxy. We perform the subtraction of foreground stars, deprojection, and resampling, as described in other NUGA papers (e.g., García-Burillo et al. 2005).

Here, we briefly recall some definitions and assumptions used to evaluate the gravitational torques. NIR images are completed in the vertical dimension by assuming an isothermal plane model with a constant scale height, equal to \( \sim 1/12 \)th of the radial scale-length of images. With a Fourier transform method we derive the potential and we assume a constant mass-to-light \((M/L)\) ratio able to reproduce the observed 12CO RCs. Beyond a radius of 20″ (or 1.96 kpc in diameter), the mass density is set to 0 in the HST-NICMOS F160W image, thus suppressing any spurious \( m = 4 \) terms. This assumption is sufficient to compute the potential over the PdBI 12CO(1–0) primary beam. For the Spitzer-IRAC 3.6 μm image, this radius truncation is done at 169″ (or 16.6 kpc in diameter).

For the non-axisymmetric part of the potential \( \Phi(R, \theta) \), we decompose \( \Phi(R, \theta) \) in Fourier components \((m\text{-modes})\), following Combes & Sanders (1981):

\[
\Phi(R, \theta) = \Phi_0(R) + \sum_{m=1}^{\infty} \Phi_m(R) \cos(m\theta - \phi_m(R))
\]

where \( \Phi_m(R) \) and \( \phi_m(R) \) are the amplitude and phase of the \( m \)-mode, respectively.

The strength of each \( m \)-Fourier component, \( Q_m(R) \), is defined by the ratio between tangential and radial forces, \( Q_m(R) = m\Phi_m(R)/F_0(R) \). The strength of the total non-axisymmetric perturbation is defined by:

\[
Q_T(R) = \frac{F_{\max}^{\text{tang}}(R)}{F_0(R)}
\]

where \( F_{\max}^{\text{tang}}(R) \) and \( F_0(R) \) represent the maximum amplitude of the tangential force and the mean axisymmetric radial force.
6.2. Evaluation of the gravity torques

The forces per unit mass ($F_x$ and $F_y$), obtained from the derivatives of $\Phi(R, \theta)$ on each pixel, allow to compute the torques per unit mass $t(x, y)$ by:

$$t(x, y) = x F_y - y F_x.$$  

The torque map is oriented according to the sense of rotation in the plane of the galaxy. The combination of the torque map and the gas density map allows to derive the net effect on the gas at each radius. Figures 22 and 23 show gravitational torque maps, computed from the HST-NICMOS F160W image, weighted by the gas surface density $t(x, y) \times \Sigma(x, y)$, normalized to their maximum value, for NUGA PdBI $^{12}$CO(1–0) and $^{12}$CO(2–1), respectively. The difference in orientation between the large-scale bar and the major axis of the galaxy ($\sim 19^\circ$ in the sky plane) implies that the deprojected difference in PAs is $\sim 35^\circ$. In both figures, the continuum line is oriented along the large-scale bar in the plane of the galaxy (PA = $35^\circ$), the dashed one orthogonally to the continuum line. In the two quadrants labeled with (+) the torques are positive, while in those labeled with (-) the torques are negative. The derived torques change sign following a characteristic 2D butterfly pattern produced by the bar. Figure 24 shows the gravitational torque map, derived from the Spitzer-IRAC 3.6 $\mu$m image, weighted by the gas surface density $t(x, y) \times \Sigma(x, y)$, normalized to their maximum value, for BIMA $^{12}$CO(1–0). The observed gas distribution is representative of the time spent by a molecular cloud on a typical orbit at this location.

By using $\Sigma(x, y)$ as the actual weighting function, we first compute the torque per unit mass averaged over azimuth:

$$t(R) = \frac{\int_0^{\Delta R} \Sigma(x, y) \times (x F_y - y F_x) \, dx}{\int_0^{\Delta R} \Sigma(x, y) \, dx},$$

where $t(R)$ is, for definition, the time derivative of the specific angular momentum $L$ of the gas averaged azimuthally, $t(R) = dL/dt |_{\theta}$. Then, to have dimensionless quantities, we normalize this variation of angular momentum per unit time to the angular momentum at this radius and to the rotation period. Finally, we estimate the efficiency of the gas flow as the average fraction of the gas specific angular momentum transferred in one rotation ($T_{rot}$) by the stellar potential, as a function of radius:

$$\frac{\Delta L}{L} = \frac{dL}{dt} \bigg|_{\theta} \times \frac{1}{L} \times T_{rot} = \frac{t(R)}{L_0} \times T_{rot},$$

where $L_0$ is assumed to be well represented by its axisymmetric estimate, $L_0 = R \times v_{rot}$. Figures 25 show $\Delta L/L$ curves computed with the HST-NICMOS F160W image for NGC 3627 derived from the PdBI $^{12}$CO(1–0) [left] and the $^{12}$CO(2–1) [right] data. The (red) dashed area corresponds to the resolution limit of our observations. In the left panel, the $^{12}$CO(1–0) map resolution is $\sim 125$ pc, while in the right panel the $^{12}$CO(2–1) map resolution is $\sim 59$ pc. In the right panel, the (green) vertical dashed line at 0.51 kpc indicates the $^{12}$CO(2–1) FOV at the PdBI. These figures show that the torques are negative within the inner 0.4 kpc.
**Fig. 25.** The torque, or more precisely the fraction of the angular momentum transferred from/to the gas in one rotation ($dL/L$), computed with the HST-NICMOS F160W image, is plotted for $^{12}$CO(1–0) [left] and $^{12}$CO(2–1) [right]. The (red) dashed area corresponds to the resolution limit of our observations. In the left panel, the limiting factor is the $^{12}$CO(1–0) map resolution ($\sim$125 pc), while, on the right, the $^{12}$CO(2–1) map resolution ($\sim$59 pc). In the right panel, the (green) vertical dashed line at 0.51 kpc indicates the $^{12}$CO(2–1) FOV at the PdBI.

**Fig. 26.** Left panel: Our NUGA PdBI $^{12}$CO(1–0) contours overlaid on the HST-NICMOS F160W image of NGC 3627 in false color. The inner 40'' are shown. Right panel: Same as left panel but for the $^{12}$CO(2–1) line.

down to the resolution limit of our observations, and reach a (negative) peak at 0.2 kpc for both $^{12}$CO(1–0) and $^{12}$CO(2–1). For $^{12}$CO(1–0), they oscillate and become negative again at 700 pc. This second (negative) peak is not present in $^{12}$CO(2–1), because it is outside the $^{12}$CO(2–1) FOV. Figures 26 show NUGA PdBI $^{12}$CO(1–0) [left] and the $^{12}$CO(2–1) [right] contours overlaid on the HST-NICMOS F160W image. This figure clearly shows that the gas is leading the bar (the sense of the rotation is direct) since the PA of the bar is $-21^\circ$, while the bulk emission of the molecular gas is distributed along a bar-like structure with a PA of 14° for the $^{12}$CO(1–0) line and of 15° for the $^{12}$CO(2–1) one (see Fig. 8 and Sect. 4.4). This explains the negative torques observed in Figs. 25.

Figure 27 shows the large-scale $\Delta L/L$ curves computed with the Spitzer-IRAC 3.6 μm image and the BIMA-SONG images. The (blue) dashed area corresponds to the resolution limit of BIMA observations, $\sim$670 pc. In this figure, the torques are negative within the inner $\sim$3 kpc, down to the resolution limit of BIMA maps, and positive at larger radii. Resonances in barred galaxies are related to the pattern speed of the stellar bar, which can be inferred from the angular velocity at the corotation (CR) radius. In early-type barred galaxies, CR is lo-
Fig. 27. The torque, or more precisely the fraction of the angular momentum transferred from/to the gas in one rotation ($dL/L$), computed with the Spitzer-IRAC 3.6 μm image, is plotted for BIMA $^{12}$CO(1–0) observations. The (blue) dashed area corresponds to the resolution limit of the BIMA observations (~670 pc).

Fig. 28. Model rotation curve $V_{\text{rot}}$ (in km s$^{-1}$) and derived frequencies $\Omega, \Omega - k/2$, and $\Omega + k/2$ (in km s$^{-1}$ kpc$^{-1}$) for NGC 3627. The (blue) vertical line indicates the stellar bar end (~3 kpc), while the (blue) horizontal one indicates the pattern speed of the bar at $\Omega_p \sim 65$ km s$^{-1}$ kpc$^{-1}$.

7. Dynamical interpretation

Figure 28 shows the model RC ($V_{\text{rot}}$) obtained from the Spitzer-IRAC 3.6 μm image, and the derived frequencies $\Omega, \Omega - k/2$, and $\Omega + k/2$ for NGC 3627. We have also derived a model RC from the HST-NICMOS F160W image, which is identical to the model RC from the Spitzer-IRAC 3.6 μm image until 1.3 kpc from the center (it is not shown in the figure because it adds no new information). The model RC has been calibrated to the Hubble RC derived from Chemin et al. (2003), to have $V = 212$ km s$^{-1}$ at 8 kpc. Fig. 28 shows that if the stellar bar ends at ~3 kpc (blue vertical line), with a pattern speed of the bar $\Omega_p \sim 65$ km s$^{-1}$ kpc$^{-1}$ (blue horizontal line) then the CR of the bar would be at ~3.3 kpc, consistent with the results of Chemin et al. (2003) who estimated the CR radius between 2.6 and 3.7 kpc. The $\Omega - k/2$ curve could be marginally compatible with an ILR at $r = 500$ pc, but because there is no clear ring signature in the morphology, we exclude the presence of an ILR. In addition, since there is a strong bar, true precessing rate is lower than the epicyclic approximation $\Omega - k/2$, and therefore the curve is only an upper limit. Hence there is probably no ILR. The absence of an ILR was already discussed in Sect. 6.2 where we elaborated such a scenario.

The pattern speed of NGC 3627 has been measured by several authors. Chemin et al. (2003) have assumed that the inner ring-like feature found by Regan et al. (2002) but not by us, corresponds to the location of an ultra-harmonic resonance. Rand & Wallin (2004), using the BIMA SONG data and the Tremaine-Weinberg method, have measured a pattern speed of the bar of $\Omega_p = 50^{+3}_{-5}$ km s$^{-1}$ kpc$^{-1}$, in good agreement with our determination.

In the presence of an ILR, the torques should be negative between the CR of the bar and the ILR. For NGC 3627, without an ILR, the torques are negative between the CR of the bar and the AGN, down to the resolution limit of our observations. Such a conclusion would be the natural outcome of a scenario in which a young and rapidly rotating bar has had no time to slow down due to secular evolution, and has not yet formed any ILR. The presence of molecular gas inside the ILR of the primary bar, or where we expect that the ILR will form, makes NGC 3627 a potential smoking gun of inner gas inflow. In this scenario, the gas there is certainly fueling the central region, and in a second step could fuel directly the AGN. Finding smoking gun evidence of AGN fueling is proving to be quite challenging, perhaps because of the short-lived nature of the mechanisms responsible.

8. Summary and conclusions

The molecular gas, traced by $^{12}$CO(1–0) and $^{12}$CO(2–1) transitions, in the interacting barred LINER/Seyfert 2 galaxy NGC 3627 is distributed along a bar-like structure of ~18′′.
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