MOLECULAR GAS STREAMERS FEEDING AND OBSCURING THE ACTIVE NUCLEUS OF NGC 1068

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ABSTRACT

We report the first direct observations of neutral, molecular gas streaming in the nucleus of NGC 1068 on scales of < 30 pc using SINFONI near-infrared integral field spectroscopy. At a resolution of 0.075, the flux map of 2.12 μm 1–0 S(1) molecular hydrogen emission around the nucleus in the central arcsec reveals two prominent linear structures leading to the active galactic nucleus from the north and south. The kinematics of the gas in these features are dominated by noncircular motions and indicate that material streams toward the nucleus on highly elliptical or parabolic trajectories, whose orientations are compatible with that of the disk plane of the galaxy. We interpret the data as evidence for fueling of gas to the central region. The radial transport rate from ~ 30 pc to a few parsecs from the nucleus is ~ 15 M⊙ yr⁻¹. One of the infalling clouds lies directly in front of the central engine. We interpret it as a tidally disrupted streamer that forms the optically thick outer part of an amorphous clumpy molecular/dusty structure which contributes to the nuclear obscuration.

Key words: galaxies: active – galaxies: individual (NGC 1068) – galaxies: kinematics and dynamics – galaxies: nuclei – galaxies: Seyfert – infrared: galaxies

Online-only material: color figures

1. INTRODUCTION

A detailed description of the distribution and kinematics of the molecular gas in the central region of Seyfert galaxies is crucial for understanding the fueling of the nucleus and the role of gas in obscuring the active galactic nucleus (AGN). NGC 1068, at a distance of 14.4 Mpc (Bland-Hawthorn et al. 1997), is the brightest Seyfert 2 galaxy and, therefore, one of the best candidates for direct investigations of the morphology and dynamics of the molecular gas neighboring an active nucleus. The idea of a rotating molecular/dusty torus surrounding a supermassive black hole emerged from the interpretation of optical spectropolarimetry of precisely this galaxy given by Miller & Antonucci (1983), which revealed scattered type-I emission from the obscured broad-line region (BLR). Since then, several near-infrared (NIR) and mid-IR observations have in fact found and begun to elucidate the physical conditions of the concentration of molecular gas and dust in the nucleus of NGC 1068 (near-IR: Young et al. 1996; Marco et al. 1997; Rouan et al. 1998, 2004; Alloin et al. 2001; Galliano & Alloin 2002; Galliano et al. 2003; Weigelt et al. 2004; Wittkowski et al. 2004; Gratadour et al. 2005, 2006; mid-IR: Bock et al. 2000, Tomono et al. 2001, 2006; Jaffe et al. 2004; Galliano et al. 2005; Mason et al. 2006; Poncelet et al. 2006, 2007), all indirectly favoring the existence of a compact molecular/dusty torus but failing to obtain a clear image of it. Alternatively, by means of mid-IR observations over the central 140 pc (2″), Cameron et al. (1993) proposed a model in which the bulk of the molecular gas and dust is located at large distances (several tens of parsecs) from the AGN. Line-of-sight (LOS) attenuation of the BLR in this case would be a mere consequence of one or more intervening molecular clouds. More recently, Jaffe et al. (2007) analyzed new interferometric mid-IR observations of NGC 1068 and found that the fitted Gaussian components to the (μ, ν) plane of the central 10 μm source resemble a disk similar to the H₂O masers (Greenhill et al. 1996). Both the dust and H₂O maser disks appear to be oriented neither perpendicular to nor aligned with the radio jet. However, one needs to be cautious when interpreting all of these observations. As they are measurements of the continuum emission, the inferred gas/dust distributions are strongly dependent on temperature, tracing in fact radiation of matter at a given temperature rather than spatial gas/dust distributions.

The 2.122 μm H2 rovibrational ν = 1–0 S(1) emission line probes hot (≥ 10⁴ K) and moderately dense (≥ 10³ cm⁻³) molecular gas and, as such, may be an excellent tracer of gas in the nuclear region. Its spatial distribution can expose the potential presence of a molecular/dusty torus, and also provide physical information on fueling or feedback mechanisms. Imaging spectroscopy of this line (Rotaciuc et al. 1991; Blietz et al. 1994) has indicated the presence of significant amounts of hot, dense, circumnuclear molecular gas extending over the central 4 arcsec, which is associated with the narrow-line clouds. The nuclear region shows a strong peak almost 1″ east of the nucleus and a weaker one ~ 1″ to the west. Furthermore, the H₂ emission at a few arcseconds from the nucleus is more extended along the major axis of the bar (Davies et al. 1998). More recently, Galliano & Alloin (2002) obtained two-dimensional spectroscopic observations of the warm molecular gas in the central 4″ x 4″ of the galaxy. They did not detect H₂ emission at the location of the K-band continuum core (which is already known to be coincident with the central engine at these scales). Instead, they confirmed the two main regions of H₂ emission at about 1″ east and west of the nucleus along a P.A. = 90° and a region with complex line profiles at ~ 50 pc north of the AGN. They interpreted the observed H₂ emission at these scales in terms of a warped disk consistent with the interpretation given by
Schinnerer et al. (2000) to millimeter interferometer maps of $^{12}$CO(2–1) emission. It is now apparent from recent SINFONI (Spectrograph for INtegral Field Observations in the Near Infrared) $H_2$ 1–0 S(1) data at these scales that simple warped disk models of the molecular gas (Schinnerer et al. 2000; Baker 2000) cannot account for the fantastic variety and detail in the morphological and kinematical structure (see Davies et al. 2006), in particular since there is a considerable amount of gas inside the inner edge of the 100 pc ring.

In order to analyze in detail the physical conditions of the warm molecular gas in the central region of an active nucleus, we have obtained adaptive-optics-assisted SINFONI integral field spectroscopic data to peer deeply into the energetic core of NGC 1068. In this paper, we focus on the observations of the molecular gas emission in the central arcsecond of the galaxy done with the smallest spatial scale of the instrument, resulting in a resolution of 75 mas, approximately seven times better than previous observations. We refer to F. Müller Sánchez et al. (2009, in preparation) for the analysis of the stars, molecular, and ionized gas in the central $3''$ of the galaxy corresponding to the rest of the results from the SINFONI observations of NGC 1068.

2. OBSERVATIONS

The data presented here were obtained during 2005–2006 using the adaptive-optics-assisted NIR integral field spectrograph SINFONI (Bonnet et al. 2004; Eisenhauer et al. 2003) on the Very Large Telescope (VLT) UT4. SINFONI simultaneously delivers spectra over a contiguous two-dimensional field of 64 × 32 pixels. The data were taken in the $H + K$ bands using two of the three possible spatial pixel scales of the instrument: 0′0125 × 0′025 and 0′05 × 0′1, respectively. The 0′0125 × 0′025 SINFONI data were taken in two sets of 2 and 1.5 hr integrations on the nights of 2005 October 21 and 2006 November 27, both using the galaxy nucleus as reference for the MACAO (Multi-Application Curvature Adaptive Optics) adaptive-optics system. In both nights, the atmospheric conditions were excellent (optical seeing of the two nights was ~0′7 and ~0′5, respectively), which allows us to obtain a resolution of 0′075 FWHM as measured from the spatially marginally resolved nonstellar continuum in the $K$ band. The 0′05 × 0′1 data were obtained on 2005 October 6. Once more, the AO module was able to correct the nucleus of NGC 1068 in a seeing of 0′6, to reach ~0′1 spatial resolution. In this case, a total of four sky and eight on-source exposures of 50 s each were combined to make the final data cube. For the 0′0125 × 0′025 and 0′05 × 0′1 data sets, the spectrograph was able, in a single shot, to obtain spectra covering the whole $H + K$ bands (approximately 1.45–2.45 μm) at a spectral resolution FWHM of 125 km s$^{-1}$ ($R$ ~ 2400) for each pixel in the 0′8 × 0′8 and 3′2 × 3′2 fields of view (FOVs).

The data were reduced using the SINFONI custom reduction package SPRED (Abuter et al. 2005). This performs all the usual steps needed to reduce NIR spectra, but with the additional routines for reconstructing the data cube. Flux calibration was simultaneously performed in $H$ and $K$ bands using a G2V star HD 20339 ($H = 6.45$, $K = 6.41$), which yielded a $K$-band magnitude of 7.73 for NGC 1068 and $H$-band magnitude of 10.18 in a 1″ aperture. The values we deduced are consistent, at similar and smaller apertures, with values found in previous studies (Rouan et al. 1998; Gratadour et al. 2006; Prieto et al. 2005). In addition, flux calibration was crosschecked with VLT NACO data in 2″–4″ apertures (F. Müller Sánchez et al. 2009, in preparation). The NACO (NAOS–CONICA: Nasmyth Adaptive Optics System (NAOS)–Near-Infrared Images and Spectrograph (CONICA)) data were further crosschecked in larger 5″–10″ apertures using Two Micron All Sky Survey (2MASS) data. Agreement between the different data sources was consistent to 15%.

3. DISTRIBUTION, KINEMATICS, AND PHYSICAL PROPERTIES OF THE MOLECULAR GAS

3.1. Molecular Gas Morphology

The molecular hydrogen emission at scales of a few arcseconds from the nucleus has been previously mapped reaching spatial resolutions down to $\sim$0′5 (Galliano & Alloin 2002). Our SINFONI data at these scales reach $\sim$0′1 resolution and reveal a complex distribution of the gas that has not been entirely observed before (Figure 1). The new data resolve the previously studied $H_2$ knots and show the presence of an off-center (Δ$r = 0′.6$ southwest from the AGN) ring of molecular gas (see Section 3.6), as well as apparently linear gas streamers leading from the ring north-northwest and south-southeast to the center. In addition, the overlay of our $H_2$ flux map and the $^{12}$CO(2–1) map from Schinnerer et al. (2000) at these scales (Figure 1) shows a very good correlation, confirming that gas distributions can be traced either by the 2.122 μm $H_2$ 1–0 S(1) emission line (hot gas) or the $^{12}$CO(2–1) emission (cold gas). In Section 3.6, we briefly discuss the morphology of the ring but refer to F. Müller Sánchez et al. (2009, in preparation) for more analysis and discussion of these results. In the following, we will concentrate on the central arcsecond (white box in Figure 1) and provide a few remarks on the connection of the linear streamers to the circumnuclear environment.

The morphology of the $H_2$ 1–0 S(1) emission in the central $0′.8 \times 0′.8$ of NGC 1068 with a resolution of $0′.075$ ($\sim 5$ pc) is presented in Figure 2. The peak of the 2.1 μm nonstellar continuum is located at the origin of the image and is represented by a crossed circle. At these scales, this can be identified as the position of the central engine (Galliano et al. 2003). At larger scales, a linear structure leading to the AGN from the north-northwest and south-southeast is the only noticeable feature in this whole region (see Figure 1). On sub-arcsecond scales near the AGN, this linear structure exhibits two prominent regions of $H_2$ emission: one overlapping the center of the nonstellar continuum and the other located $\sim 0′.35$ north of this point.

Thanks to improved spatial resolution and sensitivity, molecular gas is now detected closer and closer to the AGN, in contrast to previous observations (Galliano & Alloin 2002). In Figure 3, we show a spectrum of NGC 1068 at a spectral resolution of $R \sim 2400$, integrated over a 0′.3 × 0′.1 rectangular aperture centered at the position of the nucleus; although the continuum is quite strong in this region, the $H_2$ 1–0 S(1) line is clearly seen. We will refer to this nuclear concentration of gas as the southern tongue. It has a major axis of $\sim 17$ pc and a minor axis of $\sim 7$ pc and is elongated to the south following the south-southeast extension of the linear structure. Its major axis has a position angle of about 120°, similar to that of the $H_2O$ maser disk (Greenhill et al. 1996) and the 10 μm dust emission (Jaffe et al. 2004; Poneclet et al. 2007) on a scale of 20 mas. These three features exhibit the same misalignment with the major axis of the nuclear 5 GHz radio continuum (Gallimore et al. 2004). The $H_2$ 1–0 S(1) luminosity of the southern tongue is $1.5 \times 10^{-18}$ W m$^{-2}$ ($\sim 1 \times 10^4 L_{⊙}$).
In addition to the nuclear component designated as the southern tongue, we found another area of high luminosity in the northern part of the H$_2$ intensity map (see Figure 2). In fact, this is the brightest region of the linear structure ($\sim 1.6 \times 10^4 L_\odot$), which extends up to $\sim 0.7$ north-northwest of the central engine along a P.A. of $-14^\circ$ and apparently connects to a prominent knot in the circumnuclear ring (Figure 1). We will designate this extension of the linear structure as the northern tongue. The region north of the AGN, where apparently the northern tongue and the circumnuclear ring merge, is characterized by double-peaked line profiles (Galliano & Alloin 2002). As this region is out of the central arcsecond, we postpone its quantitative analysis to a subsequent publication (F. Müller Sánchez et al. 2009, in preparation). The H$_2$ line profiles of the small-scale data studied here do not show complex morphologies, and thus they were fitted by one Gaussian component as described in Section 3.2.

Dust emission at 12 $\mu$m from the northern tongue is present in previous mid-IR observations by Bock et al. (2000), Tomono et al. (2006), and Poncelet et al. (2007). Overlays of our two H$_2$ flux maps at different spatial scales and the 12.5 $\mu$m deconvolved image of Bock et al. (2000) are shown in Figure 4. The image taken at 12.5 $\mu$m has the highest angular resolution and the highest signal-to-noise ratio (S/N) of the mid-IR images from Bock et al. (2000). For these reasons, we have chosen to compare this image with our flux maps, in a similar way as these authors did with other data sets. We want to emphasize, however, that all mid-IR images show qualitatively the same features. In both panels of Figure 4, we assumed that the mid-IR peak is located at the position of the nucleus as defined by the NIR peak. As can be seen in the two overlays, along the northern tongue there exists good correlation between the molecular gas emission and the 12.5 $\mu$m continuum. In the right panel, a dashed line indicates the boundary of the northern tongue emphasizing this correlation. Also, the alignment gives a fair correlation between the east–west unresolved mid-IR core and the H$_2$ southern tongue. The two overlays show a bend to the east, although the mid-IR bend is more pronounced. The qualitative agreement of the two images indicates that, in the central arcsecond, the molecular gas and the dust have a similar spatial distribution that is predominantly a north–south linear structure about 1$''$ (70 pc) long which contains two bright components: the southern and northern tongues. Our observations support the interpretation given by Tomono et al.
3.2. Kinematic Evidence for Inflow

3.2.1. Detection of Noncircular Motions Around the Nucleus

We have extracted gas kinematics in the nuclear region of the galaxy from our integral field data, allowing for the first time a study of the gas motions on scales connecting the outer gas $r \sim 1''$ ($\sim 70$ pc) ring to the maser disk at $r = 0''.015$ ($\sim 1$ pc). Figure 6 shows the velocity and dispersion maps of the molecular gas in the central $0'.8 \times 0'.8$ of the galaxy. We have extracted the two-dimensional kinematics by fitting a Gaussian convolved with a spectrally unresolved template profile (an OH sky emission line) to the continuum-subtracted H$_2$ 1–0 S(1) spectral profile at each spatial pixel in the data cube. We performed a minimization of the reduced $\chi^2$ in which the parameters of the Gaussian (amplitude, center, and width in velocity space) were adjusted until the convolved profile best matched the data. The uncertainties were boot-strapped using Monte Carlo techniques, assuming that the noise is uncorrelated and the intrinsic profile is well represented by a Gaussian (Davies et al. 2007). This method allowed us to obtain uncertainties for the velocity and dispersion in the range of $\pm (5–15)$ km s$^{-1}$. The dispersion extracted by this fitting procedure is already corrected for instrumental broadening.

The velocity field shown in Figure 6 is quite complex. There is no evidence of a rotating disk around the nucleus. Instead, one can distinguish three main kinematical components: blueshifted material with an almost constant projected velocity $v_z \sim 25$ km s$^{-1}$ in the north, redshifted projected velocities between 20 and 40 km s$^{-1}$ in the south-east, and a nuclear redshifted component ($v_z \sim 90$ km s$^{-1}$) associated with the southern tongue in Figure 2. Outside these regions, the kinematics are not reliable due to the low strength of the line ($\leq 10\%$ of the flux as can be seen in Figure 2) and, therefore, they were masked out in the velocity and dispersion maps. The nuclear redshifted kinematical component appears to be connected to the south-eastern kinematical component by a ridge of emission that gradually changes its projected velocity from $\sim 30$ km s$^{-1}$ at $r = 0''.4$ to $\sim 90$ km s$^{-1}$ at $r = 0''.04$ along a P.A. of $-20^\circ$. This and the lack of a signature of rotation indicate that the gas must be streaming almost directly toward or outward from the nucleus rather than orbiting it on circular paths. Thus, any approach to reproduce the observed kinematics by a rotating or warped disk model can be excluded.

3.2.2. Quantitative Modeling

To quantify the kinematics of the region, we have modeled the observed velocities as motions of test particles under a gravitational potential comprising a central mass and an extended stellar component.

We define a three-dimensional Cartesian coordinate system in the nuclear region of the galaxy with $x$-, $y$-, and $z$-axes
representing the right ascension, declination, and LOS directions, respectively. The gravitational potential well of the system is determined by a circumnuclear mass distribution formed by the sum of a supermassive black hole of mass $M_{BH} = 1 \times 10^7 M_\odot$ (Greenhill et al. 1996), located at the origin of the system, and a stellar mass density $M_*(r) = 1 \times 10^6 r M_\odot$ pc$^{-1}$ (F. Müller Sánchez et al. 2009, in preparation; Davies et al. 2007). The gas clouds were modeled as test particles—that is, they do not have any impact on the potential—with some initial conditions $x_0$, $y_0$, $z_0$, $v_x 0$, $v_y 0$, and $v_z 0$. The initial $x_0$, $y_0$, and $v_z 0$ components of a test particle are directly obtained from the SINFONI data. Thus, the kinematic model contains three degrees of freedom (dof) corresponding to the other three Cartesian components $z_0$, $v_y 0$, and $v_x 0$. Notice that $v_z 0$ can also be considered as a variable due to the uncertainty in the observed projected velocities of $\pm 10$ km s$^{-1}$. Once the phase-space conditions of a cloud are given, the position and velocity of the cloud moving according to the Newtonian laws of motion under the influence of the assumed potential were determined at every time interval $\Delta t = 10$ yr over a period of 5 Myr. Therefore, this method creates free unperturbed Keplerian orbits fully defined by the initial values of the Cartesian components of the particle’s position and velocity.

We followed a systematic approach for the determination of the Keplerian orbits of the gas particles. First, an initial position vector $r_0$ is located inside a volume defined by the FOV and several $z_0$ components ranging from $-60$ pc to 60 pc. This interval was defined as two times the $x$ or $y$ range. It is important to point out that this volume delineates the boundaries of the initial position vectors. The resulting orbits are actually contained in a spherical volume of indefinite radius. For each $r_0$, numerous sets of velocity vectors were investigated. The initial $v_z 0$ component of a particle at any given position in space basically corresponds to the observed projected velocity at that particular spot. The tested values for $v_x 0$ and $v_y 0$ at each point in space were dependent on $r_0$ and ranged from $-\sqrt{2G M_{BH}}/r_0$ to $\sqrt{2G M_{BH}}/r_0$. This interval was established based on the universal expression for the tangential velocity $v_{tan}$ of any point on the orbit. If the magnitude of the initial tangential velocity vector is smaller than this factor, the motion will be elliptic; if it is larger, the motion will be hyperbolic; and if it is precisely this value, a parabolic orbit will be delineated. In consequence, by considering that the magnitude of its $v_x 0$ and $v_y 0$ components range from $0$ km s$^{-1}$ to the value given by this factor, all types of orbits are included. Thus, the initial conditions are just a point in the parameter space of any types of orbit of arbitrary eccentricity, size, and orientation.

The first attempts to model the kinematics showed that a single Keplerian orbit cannot reproduce the totality of $v_z$ vectors of the observed velocity field. Therefore, we decided to investigate two types of sets of initial conditions as suggested by the observed blueshifted and redshifted kinematical components: one for the northern region with $x_0 = 0 \pm 5$ pc, $y_0 = 25 \pm 5$ pc, and $v_z 0 = -25 \pm 10$ km s$^{-1}$, and one for the southern part with $x_0 = -10 \pm 5$ pc, $y_0 = -25 \pm 5$ pc, and $v_z 0 = 30 \pm 10$ km s$^{-1}$. The initial spatial coordinates $(x_0, y_0)$ of the two sets were selected based on the morphology and kinematics. At first, any good fit to the data should follow the RL. Therefore, it is reasonable to have the north and south starting points located on it. Particularly for the northern region, the initial coordinates correspond to the peak of H$_2$ emission in Figure 2. Furthermore, they are located in regions where the velocity uncertainties are low. This is once more particularly important for the northern region where the blueshifted velocities associated morphologically with the northern tongue are well recognizable. Finally, a visual inspection of the velocity field suggests that the motions closer to the nucleus are probably perturbed by other physical processes and could possibly mislead the modeling.

Approximately $5 \times 10^4$ Keplerian orbits of arbitrary eccentricity, size, and orientation were modeled for each region and compared to the observations to determine a best fit. The orbits

Figure 6. Velocity (left) and dispersion (right) maps of the molecular gas extracted from the SINFONI data cube in the central $\pm 0^\prime$4 of NGC 1068. Velocities are measured with respect to the systemic velocity. The dispersion has been corrected for instrumental broadening. In each case, a crossed circle indicates the peak of the continuum emission. The maps are binned using Voronoi tessellations (Cappellari & Copin 2003). The bins where the line properties could not be extracted were masked out and correspond to the white regions. The rejected pixels in both maps are those with a flux density lower than 10% of the peak of the central emission shown in Figure 2 and are shown in white in the right part of the fields. The open triangles show the projected trajectory of the northern concentration of gas (the northern tongue, Orbit NT2). The half-crosses show the past trajectory of the gas, which is currently located in front of the AGN (the southern tongue, Orbit ST2). (A color version of this figure is available in the online journal.)
providing the best approximations to the data at these scales can be further compared with the large-scale intensity map shown in Figure 1 in order to study the connection between the gas in the central arcsecond and the circumnuclear environment. Particularly, we will be able to test the hypothesis of gas streaming from the circumnuclear ring along the linear structure. This hypothesis could motivate a different approach for the determination of the circumnuclear ring along the linear structure. This hypoth-

### Table 1
Orbital Parameters of the Southern Gas Streamers

| Orbit | $i^\circ$ | P.A.$^a$ | $x_0^b$ | $y_0^b$ | $z_0^b$ | $v_{x0}^c$ | $v_{y0}^c$ | $v_{z0}^c$ | $x_p^d$ | $y_p^d$ | $z_p^d$ | $x_a^e$ | $y_a^e$ | $z_a^e$ | $t^f$ | $\chi^2$ |
|-------|-------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|-------|-------|
| ST1   | 30    | 90      | -11     | -25     | -14     | 6       | 35      | 20      | 0.1     | 0.42    | 0.24    | -25     | -121    | -70     | 0.9    | 0.87   |
| ST2   | 45    | 90      | -11     | -25     | -25     | -1      | 25      | 25      | -0.01   | 1.24    | 1.24    | 5       | -70     | -70     | 1      | 0.18   |
| ST3   | 60    | 90      | -11     | -25     | -42     | -1      | 17      | 30      | -0.3    | 1.07    | 1.85    | 28      | -98     | -160    | 1.1    | 0.71   |

**Notes.**

- $^a$ Inclination and position angles are given in $^\circ$.
- $^b$ Initial spatial coordinates in pc.
- $^c$ Initial velocity vectors in km s$^{-1}$.
- $^d$ Spatial coordinates of the pericenter in pc.
- $^e$ Spatial coordinates of the apocenter in pc.
- $^f$ Infalling timescale in Myr. This is defined as the time a gas cloud takes to travel from the initial coordinates to the pericenter.

### Table 2
Orbital Parameters of the Northern Gas Streamers

| Orbit | $i^\circ$ | P.A.$^a$ | $x_0^b$ | $y_0^b$ | $z_0^b$ | $v_{x0}^c$ | $v_{y0}^c$ | $v_{z0}^c$ | $x_p^d$ | $y_p^d$ | $z_p^d$ | $x_a^e$ | $y_a^e$ | $z_a^e$ | $t^f$ | $\chi^2$ |
|-------|-------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|-------|-------|
| NT1   | 30    | 90      | 0.0     | 25      | -14     | 25      | -35     | -20     | -5      | -3.7    | -2.1    | 82      | 61      | 35      | 1.3    | 1.1    |
| NT2   | 45    | 90      | 0.0     | 25      | 25      | -18     | -25     | -25     | -2.9    | -2.9    | -2.9    | 56      | 54      | 54      | 1.3    | 0.51   |
| NT3   | 60    | 90      | 0.0     | 25      | 42      | -12     | -20     | -35     | -2.4    | -1.8    | -3      | -3      | -3      | -3      | 1.1    | 2      |

**Notes.**

- $^a$ Inclination and position angles are given in $^\circ$.
- $^b$ Initial spatial coordinates in pc.
- $^c$ Initial velocity vectors in km s$^{-1}$.
- $^d$ Spatial coordinates of the pericenter in pc.
- $^e$ Spatial coordinates of the apocenter in pc.
- $^f$ Infalling timescale in Myr. This is defined as the time a gas cloud takes to travel from the initial coordinates to the pericenter.

3.2.2.3. Gas is on Highly Elliptical/Parabolic Orbits

Based on the reduced $\chi^2$ goodness-of-fit analysis described in Section 3.2.2, we found for the northern and southern regions that among the complete set of tested orbits, only highly elliptical/parabolic orbits provide good approximations to the data points ($\chi_{RL}$, $y_{RL}$, $v_z$). These orbits are contained in planes that are rotated through an axis coinciding with the $x$-axis (P.A. of the rotation axis is 90$^\circ$) and have inclinations between 30$^\circ$ and 60$^\circ$. These results confirm the presence of gas streamers in the nucleus of NGC 1068. The initial conditions and other parameters of three representative orbits of the southern region are shown in Table 1. The same information for three orbits of the northern region is presented in Table 2. The trajectories of the six orbits in the projected plane of the galaxy are shown in Figure 7, plotted over the intensity map. As can be seen in the left panel of this figure, the southern orbits are spatially associated with the southern tongue, and thus they are identified in Table 1 as orbits/streamers ST1, ST2, and ST3. The northern orbits are clearly associated with the northern tongue (right panel of Figure 7), and therefore they are designated as orbits/streamers NT1, NT2, and NT3.

The $v_z$ components of the six orbits are presented in Figure 8. For comparison, velocity curves of the data were extracted along the trajectories of the streamers. As these velocity curves are all similar, only those corresponding to orbits ST2 and NT2 are plotted in the left and right panels of Figure 8, respectively. As can be seen in the two panels of this figure, there is good agreement between the models and the data within the error bars. The velocity of the gas that is now lying in front of the nucleus corresponds to that of the southern streamer. This is demonstrated in both panels of Figure 8 and in the left panel of Figure 6, which shows the trajectories of orbits ST2 and NT2 plotted over the velocity map. It can be seen in this figure that the southern redshifted component is connected to the nuclear kinematic component along the streamer trajectory. For the northern region, the projected velocities of the models fit the data well until $r \sim 0.17$ parsec. Within this radius the velocities of the streamer are not recognizable as they are being hidden by the nuclear redshifted kinematical component formed basically by the southern streamer and motions resulting from cloud–cloud collisions at a few parsecs from the nucleus.
Figure 7. Left: trajectories of orbits ST1 (red curve), ST2 (blue curve), and ST3 (green curve) plotted over the intensity map in a black–white color scale. Right: trajectories of orbits NT1 (red curve), NT2 (blue curve), and NT3 (green curve) plotted over the intensity map in a black–white color scale. The peak of the nonstellar continuum is represented by a crossed circle in both panels. The bins where the line properties could not be extracted were masked out and correspond to the diagonal patterned regions in both images.

(A color version of this figure is available in the online journal.)

Figure 8. LOS velocities ($v_r$) of the streamers. The left panel shows orbits ST1 (red dashed line), ST2 (blue dashed-dotted line), and ST3 (green dotted line). The right panel shows orbits NT1 (red dashed line), NT2 (blue dashed-dotted line), and NT3 (green dotted line). In the left panel, the black solid line corresponds to the velocity curve extracted from the data along the trajectory of orbit ST2 starting at $r = 0''$ until $r = 0''015$ (1 pc). In the right panel, the black solid line corresponds to the velocity curve extracted from the data along the trajectory of orbit NT2 starting at $r = 0''35$ until $r = 0''2$ (14 pc). The jet–cloud interaction in the north takes place at $r \sim 0.25$, and is indicated by a red circle in the right panel.

(A color version of this figure is available in the online journal.)

We evaluate the goodness of fit to the RL and the projected velocities by means of the reduced $\chi^2$ analysis discussed in Section 3.2.2. The results are shown in Tables 1 and 2. During the fitting process, it became clear that the somewhat large uncertainties in the velocity values influence the calculation of the reduced $\chi^2$. In consequence, the best fit corresponds to the orbits presenting the minimum $\chi^2$. This was found for orbits ST2 and NT2 for the southern and northern regions, respectively. The conclusion arising from the orbital fits is that in the central arcsecond of NGC 1068, there exist gas streamers flowing along the southern and northern tongues in a plane that is rotated around an axis with a P.A. = 90$^\circ$ and has an inclination of 45$^\circ$.

3.2.4. Streamers Flow Inward in the Plane of the Galaxy

The orientation of the planes of the orbits discussed in Section 3.2.3 is so that the top half is on the far side and the bottom half toward us. However, the same fits to ($x_{RL}$, $y_{RL}$, $v_z$) are obtained for orbits located in planes that have the opposite orientation to the one presented in Tables 1 and 2 (negative inclinations). In other words, based only on the kinematic modeling, there are two sets of orbits that we cannot distinguish: those in which the gas is heading toward the nucleus, that is, the gas is streaming inward (positive inclinations), and those in which the gas is flowing away from it, that is, the gas is streaming outward (negative inclinations). Luckily, our data combined with previous observations provide enough evidence to break this degeneracy.

As demonstrated by several authors, the northeast radio jet falls on the near side and its southwest counterpart on the far side of the galaxy disk (e.g., Gallimore et al. 1994). The northeast jet exhibits a bending point in its way out of the galactic plane caused by a shock interaction between the jet and a dense molecular cloud (Gallimore et al. 1996; Tecza et al. 2001; Cecil et al. 2002; Poncelet et al. 2007). The direct evidence for the molecular cloud obstructing the way of the jet in our SINFONI data (Figure 5) indicates that the orientation of the plane containing the cloud must be compatible with that of the galaxy plane: that is, the top half is on the far side and the bottom half toward us. In consequence, the gas transport is toward the nucleus: that is, the gas is streaming inward.

We can compare this scenario with previous observations of this galaxy. According to the “NGC 1068 Ringberg standards” (Bland-Hawthorn et al. 1997), the galaxy disk has an inclination of $i = 40 \pm 3^\circ$ and a kinematic major axis close to 90$^\circ$. A similar configuration was found by the kinematics of the stars observed at $r = 3''$ ($\sim 200$ pc) with SINFONI (F. Müller Sánchez et al. 2009, in preparation; Davies et al. 2007). These authors found that a rotating disk model with a P.A. = 84 $\pm 4^\circ$ and $i = 45 \pm 4^\circ$ well reproduces the stellar kinematics. At scales down to $r = 0.5$, the stellar velocity field is compatible with the same kinematic major axis but the inclination is not well constrained. This situation is similar to what we have found for the gas, although our modeling favors an inclination of 45$^\circ$.

The orientation is consistent with the strong evidence across the electromagnetic spectrum that the northeast radio jet,
ionization cones, and the extended X-ray emission fall on the near side, and the southwest counterparts of all of these fall on the far side, and are therefore hidden by the galaxy disk (Bland-Hawthorn et al. 1997). Finally, the plane orientation of our model is also consistent with the recent H2 observations of Galliano & Alloin (2002) who reproduced the observed changes in the line profiles across the 200 pc central region by a two-component kinematical model consisting of a rotating molecular disk inclined 65° with this orientation plus an outflow.

Thus, the resulting physical model consists of gas streamers located in the plane of the galaxy, and falling inward from either side of the nucleus. The streamer in all cases approaches the center (pericenters of a few pc), but as far as we can tell with the present spatial resolution, it does not actually reach the point source (see Tables 1 and 2). However, cloud–cloud collisions at a few parsecs from the nucleus may provide a mechanism through which orbiting gas can lose angular momentum and remain in the inner region, eventually falling to the center. Additionally, it can be seen in the right panel of Figure 6 that the streamers constitute a σ-dip in the whole field and thus are cold, indicating that the gravity dominating the overall flow velocity is stronger than the internal dispersion. The tidal stretching of the material during infall produces the streamers now observed as a linear structure. These motions are strong evidence that we are seeing, on scales down to a few parsecs, how gas is being driven toward the AGN in NGC 1068, and hence how the AGN is being fuelled.

3.3. Mass of the Infalling Molecular Material

We now discuss the molecular gas masses of the southern and northern tongues. The lack of robust direct probes of the gas mass complicates the analysis. To mitigate the uncertainties, we have used several independent methods.

Our first estimate is based on the dynamical mass obtained by Davies et al. (2007) from the stellar kinematics in the central second of the galaxy. A dynamical mass of \( M_{\text{dyn}} = 1.3 \times 10^8 \, M_\odot \) within \( r = 0.5 \) (35 pc) is given by these authors. Assuming a conservative 10% gas fraction (Hicks et al. 2009) and that most of the gas mass within this radius is distributed in equal amounts inside the southern and northern tongues (see Figure 2), each of these components would then have a mass of \( \sim 6 \times 10^7 \, M_\odot \). This value can be considered as a lower limit due to the small adopted gas fraction, which probably is higher in the nuclear regions of Seyfert 2 galaxies (Hicks et al. 2009).

However, assuming that the gas particles in each of the two tongues initially had a spherical geometry, we can estimate a dynamical mass directly from the dispersion velocity from the relation \( M_{\text{dyn}} = 5\sigma^2 r / G \) (Bender et al. 1992). Considering a sphere with radius \( r = 0.1 \) (7 pc) based on the approximate FWHM of the southern tongue, and \( \sigma = 70 \pm 15 \) km s\(^{-1}\) as measured from the dispersion map along the trajectories of the streamers (Figure 6), we find a mass of \( 6.5 \pm 0.1 \times 10^7 \, M_\odot \) for each concentration of molecular gas. The obtained value represents an upper limit on the gas mass since this calculation implicitly assumes that the gas is gravitationally bound, and this may not be the case.

A third independent method to estimate the mass of the molecular gas in the region is from the H2 1–0 S(1) luminosity and an appropriate conversion factor between this quantity and \( M_{\text{gas}} \). Müller Sánchez et al. (2006) found a ratio of \( L_{1–0 \, S(1)} / M_{\text{gas}} = 2.5 \times 10^5 \, L_\odot / M_\odot \) from large aperture (3′ or more) measurements of actively star forming galaxies (including NGC 1068). Although this ratio was obtained for conditions that are probably not met in the nuclear region of the galaxy and depends on fraction of gas on cloud surfaces that can be heated, we apply it simply because there is evidence of vigorous star formation close to the AGN (F. Müller Sánchez et al. 2009, in preparation; Thatch et al. 1997; Davies et al. 2007) and it can help us to make at least an approximate estimate of the total molecular gas mass. From the total H2 1–0 S(1) luminosity of the northern and the southern tongue, we estimate the total gas mass of each component to be \( 6 \times 10^7 \, M_\odot \) and \( 4 \times 10^7 \, M_\odot \), respectively. The uncertainties in this approach correspond to the uncertainties in the conversion factor, which has a 1σ statistical uncertainty from the 17 galaxies in their sample of a factor of 2. However, this factor has additionally a systematic uncertainty inherent to the probable overestimated gas masses of the galaxies in the table from Müller Sánchez et al. (2006) obtained using a standard CO–H2 conversion factor (overestimation of factors of 2–5). This would lead to masses for the northern and the southern tongues as little as \( 6 \times 10^6 \, M_\odot \) and \( 4 \times 10^6 \, M_\odot \), respectively. A similar conversion factor between cold and warm gas masses is proposed by Dale et al. (2005) for NGC 1068 \( M_{\text{gas}}^{\text{warm}} / M_{\text{H2}} = 1 \times 10^{-6} \). After converting the H2 1–0 S(1) luminosities to warm gas masses (Dale et al. 2005), we obtain total gas masses which are very consistent with the values calculated by means of the ratio \( L_{1–0 \, S(1)} / M_{\text{gas}} \).

The X-ray irradiation of molecular clouds by the central X-ray source in NGC 1068 has been discussed by Maloney (1997) and Matt et al. (1997); also see Neufeld et al. (1994). Maloney et al. found that an attenuating column density of \( 10^{22} \) cm\(^{-2}\) between the central engine and the H2 emitting molecular clouds in the central \( r \sim 100 \) pc accounts for the observed H2 intensity. As the gas density is a function of radius, it is probable that the column density is increased at our scales \( r = 35 \) pc. Matt et al. (1997) have shown that the opaque material that obscures our direct view to the central engine of NGC 1068 is Compton thick with an attenuating column density of at least \( N_H = 10^{24} \) cm\(^{-2}\). However, this does not imply that the H2 clouds have precisely, or even approximately, this value. By assuming this and \( 10^{23} \) cm\(^{-2}\) as the upper and lower limits of the averaged column density in the central \( r = 0.4 \) pc, respectively, we find that the southern/northern tongue has a gas mass ranging from \( 2 \times 10^6 \) to \( 2 \times 10^7 \, M_\odot \).

Our last method for determining the gas masses is based on the dust emissivity at mid-IR wavelengths. Recent mid-IR observations from Tomono et al. (2006) inferred a value of \( 4.6 \times 10^5 \, M_\odot \) for the dust mass in the northern tongue. As the total gas mass is expected to be \( \sim 100 \) times greater than the dust mass (Contini & Contini 2003; Draine 2003), a value of \( 4.6 \times 10^7 \, M_\odot \) can be inferred for the gas mass in this component. Assuming once more that the two gas concentrations have basically the same mass, the southern tongue will have also a gas mass of \( \sim 4.6 \times 10^7 \, M_\odot \).

We can compare the values derived from the five different methods with previous estimates of the gas mass in the nuclear region of NGC 1068. From millimeter/sub-millimeter interferometry, Tacconi et al. (1994) estimated the total mass contained within 1′ of the nucleus as \( \sim 1.6 \times 10^6 \, M_\odot \). More recent interferometric observations of the \(^{12}\)CO(1–0) and \(^{12}\)CO(2–1) emission by Schinnerer et al. (2000) gave a molecular mass of \( \sim 5 \times 10^7 \, M_\odot \) contained in the central 100 pc of the galaxy. In addition, radiative transfer theoretical models from Schartmann et al. (2005) predicted a dust mass of \( 8 \times 10^4 \, M_\odot \) in the central 70 pc, which converted to gas mass results in a value of \( 8 \times 10^5 \, M_\odot \).
All estimates are plausibly consistent with each other and with previous approximations, suggesting that each molecular gas concentration (the southern or the northern tongue) has a mass within the range $6 \times 10^6 - 6 \times 10^7 M_\odot$ with a logarithmic mean of $2 \times 10^7 M_\odot$ and a statistical uncertainty of a factor of 3. We will adopt this value for the mass of each component. This is consistent with a 25% gas fraction of the dynamical mass in the central arcsecond of the galaxy (F. Müller-Sánchez et al. 2009, in preparation; Tacconi et al. 1994; Thatte et al. 1997; Schinnerer et al. 2000; Davies et al. 2007). Furthermore, it is consistent with the molecular mass estimated from $^{12}$CO(2–1) emission (Schinnerer et al. 2000) on slightly larger scales and an averaged column density in the central $\pm 0.4$ of $10^{24}$ cm$^{-2}$.

### 3.4. Mass Accretion Rate

The morphology and kinematics of the gas are strong evidence that we are witnessing, on scales of a few parsecs, how gas is being driven toward the AGN in NGC 1068, and hence how the nucleus is being fuelled.

The mass accretion rate down to a few parsecs from the AGN can be estimated by assuming that material falls into the nucleus through the linear structure. The infalling timescale, defined as the time a gas cloud takes to travel from the initial position to the pericenter, is directly obtained from the modeling and has a value of 1.3 Myr for the northern streamer (see Table 2). This factor and the total gas mass yield a mass accretion rate at these scales of $\sim 15 M_\odot$ yr$^{-1}$ with a 1$\sigma$ uncertainty of a factor of 3. This value is an upper limit since not all the gas flowing toward the nucleus will actually stay there. A similar value is found for the southern streamer assuming that its mass corresponds to the mass that is currently located in front of the nucleus. From millimeter interferometry, Tacconi et al. (1994) estimated this influx to be a few $M_\odot$ yr$^{-1}$ from the total mass contained within 1$\prime$ of the nucleus ($\sim 1.6 \times 10^8 M_\odot$) and radial velocities ($\sim 50$ km s$^{-1}$), which is of the same order as our data.

We can compare this inflow rate on scales of $\sim 10$ pc with that onto the black hole itself. The mass accretion rate at scales down to one Schwarzschild radius $R_S$ can be estimated from the mass-to-luminosity conversion efficiency of a black hole $L = \eta \epsilon^2 dM/dt$, where $\eta$ is the accretion efficiency with typical values of 0.1–0.3 (Eardley & Press 1975) and $L$ is the bolometric luminosity of the AGN, which for NGC 1068 is $\sim 8 \times 10^{44}$ erg s$^{-1}$ (Telesco & Harper 1980). This yields a mass accretion rate of $0.03–0.09 M_\odot$ yr$^{-1}$, indicating that $dM/dt$ is reduced $\sim 1000$ times from $r = 1$ pc to a few $R_S$. An analogous situation is observed at our own Galactic Center, for which mass accretion rates of $10^{-3}–10^{-4} M_\odot$ yr$^{-1}$ at $r = 1$ pc are observed (Genzel & Townes 1987), and $dM/dt \sim 10^{-7}–10^{-8} M_\odot$ yr$^{-1}$ at a few $R_S$ from the point source Sgr A* are estimated for a bolometric luminosity of the point source of a few $10^{36}$ erg s$^{-1}$ (Ozernoy & Genzel 1996; Marrone et al. 2007). The apparent $dM/dt$ is a strong function of radius, with much reduced $dM/dt$ closer to the nucleus. Qualitatively, this is a natural consequence of inefficient angular momentum transport. While this may be a coincidence, we speculate that the gas accretion mechanisms are similar for active and nonactive supermassive black holes. Recent simulations of accretion of stellar winds onto Sgr A* (Cuadra et al. 2006) and supermassive black holes in Seyfert nuclei (Schartmann 2007) revealed that the cold gas streamed down to scales approximately ten times smaller and settled into a very turbulent disk. This suggests that indeed both the processes, helping and hindering gas inflow, are the same for Seyfert galaxies and the Galactic Center, respectively.

### 3.5. Obscuration by Inflowing Gas

We now discuss the implications of the presence of molecular gas in front of the nucleus to the obscuration of the AGN in NGC 1068. First, we calculate the gas mass surface density $\Sigma$ of the southern tongue assuming once again a cloud radius of $R = 0.1\prime$. For a gas mass of $2 \times 10^7 M_\odot$, we obtain $\Sigma = 12 \times 10^4 M_\odot$ pc$^{-2}$, yielding a column density of $N_H = 8 \times 10^{24} \text{cm}^{-2}$, which is comparable with the values predicted for highly-absorbed objects ($N_H \geq 10^{24} \text{cm}^{-2}$) and specifically for Compton thick sources, such as NGC 1068 (Bassani et al. 1999; Matt et al. 1997), and the column densities of clumpy torus models (Nenkova et al. 2002). This high column density suggests that the nuclear structure is optically thick in the NIR and, hence, this gas concentration can be associated with the obscuring material that hides the BLR. In addition, as this value represents an average on scales of $\sim 0.2\prime$, the true column density of individual smaller clouds must be larger. The fact that a considerable amount of the 2$\mu$m and 10 $\mu$m emission from the innermost region ($\sim 1$–2 pc) and the maser disk radiation is not obscured despite the presence of large gas column densities implies that the structure must be a clumpy medium. LOS attenuation of all of these in this case would be a mere consequence of one or more intervening molecular clouds.

Our observations therefore suggest that the southern tongue can be associated with the obscuring material that hides the nucleus but not in the classical picture of a rotating torus. This scenario is mainly ruled out by the kinematics which do not show any type of rotation near the AGN. However, there are several pieces of evidence that support this association. First, the size scale of the nuclear gas is remarkably similar to those of recent mid-IR observations (Bock et al. 2000; Tomono et al. 2001, 2006; Galliano et al. 2005; Poncelet et al. 2007) and those of static torus models, in particular the latest clumpy model of Höning et al. (2006), for which a size of $15 \times 7$ pc (diameter) is predicted for the H$_2$ distribution in this galaxy (S. Höing 2007, private communication). There is also a similarity between the P.A. of the major axis of the core, $\sim 120^\circ$, which is consistent with that of the line of maser spots (Greenhill et al. 1996) and the 300 K dust emission (Jaffe et al. 2007). Furthermore, the estimated gas mass and column density fully agree with previous observations and torus models (see Section 3.3). Hence, we interpret this nuclear concentration of gas as a set of infalling clouds that form the optically thick outer part of an amorphous clumpy molecular/dusty structure. This large-scale structure that we have observed will most probably enclose smaller clouds, qualitatively similar to a nested clouds scenario in which a distinct rotating molecular/dusty torus may or may not be present. In any case, based on the morphology and kinematics of the gas, we can state that if there is a rotating torus in NGC 1068, its outer radius $R_{out}$ must be smaller than 7 pc and it is encircled by this amorphous molecular/dust obscuration.

### 3.6. Connection of the Streamers with the Circumnuclear Environment

The remaining subject to investigate is the origin of the infalling material. A detailed study of the physical conditions of the NLR and the molecular gas at larger scales is crucial for the understanding of this phenomenon. We postpone our analysis of these and other features in the central $3\prime \times 3\prime$ of NGC 1068 to a subsequent publication (F. Müller-Sánchez et al. 2009, in preparation). Here, we provide a few remarks on
The previous analysis has not only elucidated a plausible connection of the gas streamers with the circumnuclear environment, but also confirmed the results obtained from the $\chi^2$ goodness-of-fit analysis. On one hand, the large-scale study suggests that orbit ST3 is not a good fit to the data at these scales as most of its trajectory is actually observed in the empty cavity of the emission map where very little gas is detected. This and the fact that the origin of orbit NT3 is uncertain imply that the gas is with high probability not contained in orbits with inclination angles close to 60$^\circ$. On the other hand, if one asserts that the gas originates in the ring, orbits with 30$^\circ$ inclination (ST2 and NT2) are shown in orange. Orbits with 60$^\circ$ inclination (ST2 and NT2) are shown in orange. Orbits with 45$^\circ$ and NT1) are represented by red curves. Orbits with 45$^\circ$ inclination (ST2 and NT1) are shown in orange. Orbits with 60$^\circ$ inclination (ST3 and NT3) are represented by green curves. The location of the AGN, as indicated by the peak of the nonstellar continuum, is represented by a white crossed circle. The initial spatial coordinates ($x_0$ and $y_0$) of the orbits are indicated by small white circles. The white inner and outer concentric ellipses delineate the thickness of the molecular ring. The central white ellipse is only plotted for reference.

(A color version of this figure is available in the online journal.)

Figure 9. Complete trajectories of the six orbits described in Tables 1 and 2 plotted over the large-scale $\text{H}_2$ intensity map. Orbits with 30$^\circ$ inclination (ST1 and NT1) are represented by red curves. Orbits with 45$^\circ$ inclination (ST2 and NT2) are shown in orange. Orbits with 60$^\circ$ inclination (ST3 and NT3) are represented by green curves. The location of the AGN, as indicated by the peak of the nonstellar continuum, is represented by a white crossed circle. The initial spatial coordinates ($x_0$ and $y_0$) of the orbits are indicated by small white circles. The white inner and outer concentric ellipses delineate the thickness of the molecular ring. The central white ellipse is only plotted for reference.

The possible connection of the streamers with the circumnuclear environment.

In the central arcsecond, the orbital fit shows that highly elliptical/parabolic orbits in the plane of the galaxy reproduce the ridge and velocities of the gas quite well. A visual inspection of Figure 1 shows that, apparently, the central two streamers are part of a linear structure connecting the north-northeast and south-southwest to the circumnuclear ring. We can test this hypothesis by comparing the complete trajectories of the orbits with the larger-scale $\text{H}_2$ emission map in Figure 1. A streamer is consistent with an origin in the ring if its apocenter lies inside the ring. If the apocenter of the orbit lies outside the ring, a ring origin of the streamer is uncertain. In order to have a reference width of the ring, we have superimposed on the intensity map several concentric thin rings of different sizes but having the same axis ratio and position angle as the observed ring in Figure 1. Based on the width of brightest $\text{H}_2$ emission around the ring, this overlay suggests that one can assign a characteristic thickness to the ring of $\sim 0.6$ (42 pc).

The results of this investigation for the six orbits described in Table 1 and 2 are shown in Figure 9. In this figure, we have plotted the complete trajectories of the orbits over the larger-scale $\text{H}_2$ flux map presented in Figure 1. However, as the gas streams inward, we observe only the part of each orbit that transports gas to the nucleus (the eastern part of each orbit). Based on the results from the $\chi^2$ goodness-of-fit analysis, we primarily considered orbits with 45$^\circ$ inclination. As can be seen in Figure 9, orbit NT2 follows the northern part of the linear structure until it apparently merges with the circumnuclear ring. The rest of the streamer’s trajectory is fully contained in the ring implying that the streamer is consistent with an origin in the circumnuclear ring. In the southern region, orbit ST2 follows the nearly linear extension of the southern tongue until $r \sim 0.6$. After this point, the linear structure is not distinguishable anymore from the several filaments and knots of gas which appear to be emanating from the ring. In this case, as the apocenter of the orbit is contained in the ring (note that the width of the ring can be slightly larger), streamer ST2 is also consistent with an origin in the circumnuclear ring.

Whether the circumnuclear ring is contained in the plane of the galaxy as the streamers or in another configuration is presently uncertain. Assuming a ring origin for the streamers, and that the circumnuclear ring is contained in the plane of the galaxy as suggested by previous authors (Schinnerer et al. 2000; Galliano & Alloin 2002), for the material in the ring to approach the center, collisions must remove a significant fraction of the angular momentum. There is strong evidence that gas in the ring exhibits significant noncircular motions (Galliano & Alloin 2002; Davies et al. 2006). This could result in collisions that lead to loss of sufficient angular momentum. Such nonrotating clouds would likely collide with orbiting material in the ring at a stationary point in space; the gas torn off the ring would originate at this stationary point, and so should follow a time-independent path. The tidal stretching of the material during infall produces the streamers now observed as a linear structure. However plausible this scenario may seem, it remains speculative at this point. A better understanding of the physical properties of the circumnuclear ring is required. Thus, as mentioned above, we postpone any interpretation of the ring to a subsequent paper (F. Müller Sánchez et al. 2009, in preparation).

4. CONCLUSIONS

In this paper, we have presented high-resolution SINFONI observations of the molecular gas in the nucleus of NGC 1068. The distribution of the $\text{H}_2 1–0 \text{S(1)}$ emission at a resolution of 0′′075 has been resolved. Two bright regions connected by a linear structure extending up to 0′′7 north of the nucleus along a P.A. of $\sim −14^\circ$ are distinguished: one lying right in front of the nucleus (the southern tongue) and the other one 0′′35 north of the center (the northern tongue). The northern tongue correlates with the mid-IR emission and its tip coincides with a knot of radio continuum emission providing direct evidence of the shock interface between the jet and a molecular cloud that has caused the jet direction to change. The main results of our analysis on the kinematics of these components are summarized as follows.

1. Dynamical modeling shows that material streams toward the nucleus. The infalling gas is contained on elliptical/parabolic orbits whose orientation is consistent with that of the plane of the galaxy. We interpret this as strong evidence of how gas, on scales of a few parsecs, fuels the AGN.
2. The gas transport is from ~ 70 pc to a few parsecs from the nucleus in the plane of the galaxy. The modeling reveals the existence of two streamers: a northern streamer associated with the northern tongue that passes very close to the nucleus (pericenter of 5 pc), and a southern streamer that currently lies in front of the nucleus associated with the southern tongue and has a pericenter of ~ 1 pc.

3. The mass inflow rate $dM/dt$ is $\sim 15 M_\odot$ yr$^{-1}$ from scales of 30 pc to a few pc. This is about 1000 times of that from a few pc to a few times the Schwarzschild radius $R_S$. A similar change in the mass inflow rate with the radius is observed in the Galactic Center. This may be a natural consequence of inefficient angular momentum transport.

4. The geometry, kinematics, and high column density of the molecular concentration of molecular gas (the southern tongue) can be explained by a tidally disrupted streamer consisting of a set of infalling clouds that form the optically thick outer part of an amorphous clumpy molecular/dusty structure.

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