Velocity-inverted Three-dimensional Distribution of the Gas Clouds in the Type 2 AGN NGC 1068

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Abstract

Spatially resolved velocity maps at high resolutions of 1–10 pc are becoming available for many nearby active galactic nuclei (AGNs) in both optical/infrared atomic emission lines and submillimeter molecular lines. For the former, it is known that a linear relationship appears to exist between the velocity of the ionized gas clouds and the distance from the nucleus in the inner ~100 pc region, where these clouds are outflowing. Here we demonstrate that, in such a case, we can actually derive the three-dimensional (3D) geometrical distribution of the clouds directly from the velocity map. Revisiting such a velocity map taken by the Hubble Space Telescope for the prototypical Type 2 AGN NGC 1068, we implement the visualization of the 3D distribution derived from the map, and show that this inner narrow-line region has indeed a hollow-cone structure, consistent with previous modeling results. Quite possibly, this is the outer extended part of the polar elongated dusty material seen in the recent mid-infrared interferometry at parsec scale. Conversely, the latter small-scale geometry is inferred to have a hollow-cone outflowing structure as the inward extension of the derived 3D distribution above. The AGN obscuring “torus” is argued to be the inner optically thick part of this hollow-cone outflow, and its shadowed side would probably be associated with the molecular outflow seen in certain submillimeter lines. We discuss the nature of the linear velocity field, which could be from an episodic acceleration that occurred ~10^7 yr ago.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Supermassive black holes (1663); Seyfert galaxies (1447); Interferometry (808)

1. Introduction

Studies of the distribution and kinematics of material in active galactic nuclei (AGNs) are quite central to understanding the physics of accretion and ejection phenomena around supermassive black holes. At 100 pc scales, the kinematics of the inner narrow-line region (NLR) have been spatially resolved by Hubble Space Telescope (HST) and subsequent ground-based integral-field-unit instruments (e.g., Hutchings et al. 1998; Crenshaw & Kraemer 2000; Cecil et al. 2002; Müller-Sánchez et al. 2011). This is now becoming even more important to studies of the inner parsec and subparsec-scale structure, since recent mid-infrared (mid-IR) interferometry has shown that even at a parsec scale, the structure is elongated in the polar direction of the narrow-line region (NLR), rather than an equatorial direction (Hönig et al. 2012, 2013; Tristram et al. 2014; López-Gonzaga et al. 2014, 2016). This polar elongation is interpreted to be due to a polar dusty outflow (Hönig et al. 2012, 2013). The mid-IR polar elongation is also seen at scales slightly larger than parsec (Asmus et al. 2016; Asmus 2019). It is quite likely that this parsec-scale structure is closely related to the polar structure at 100 pc scale, and conversely, the latter structure and kinematics are quite important and constraining on such a small scale.

Furthermore, at submillimeter wavelengths, high-resolution kinematics are now becoming available from Atacama Large Millimeter/submillimeter Array (ALMA) data (e.g., Gallimore et al. 2016; García-Burillo et al. 2016, 2019; Imanishi et al. 2018; Impellizzeri et al. 2019). The relation between the kinematics of the cold molecular gas and the warm/hot ionized gas has been investigated with matched spatial resolutions (see Hönig 2019 and references therein).

The spatially resolved velocity maps of the NLR have shown that, in the innermost 100 pc (or ~1"), there seems to be a linear relationship between the radial velocity and the projected distance from the nucleus (Crenshaw & Kraemer 2000; Das et al. 2006, 2007). This has been interpreted in such a way that the velocity of the gas clouds is proportional to the distance from the nucleus, i.e., \( v = kr \) in the three-dimensional (3D) space, with this inner region being called an “acceleration region.” Furthermore, based on the radial velocities from the two-dimensional (2D) spectra at different slit locations, it has been inferred that the spatial distribution of the line emission in 3D has a hollow-cone structure. Therefore, in these previous studies, modeling has been done in such a way that the most likely parameters, such as opening angle and inclination, have been determined assuming a hollow-cone geometry.

Based on these studies, here we demonstrate that the 3D distribution can rather directly be derived from the data, if the linear (or some power-law form) velocity field is assumed. Such a directly derived, empirical 3D distribution would uniquely be beneficial to studies of the inner structure. Revisiting the data for the prototypical Type 2 AGN NGC 1068 taken with HST, we reconstruct and visualize such a 3D distribution directly from the data, and study the structure in detail. We further discuss the implications of the derived distribution.

The systemic velocity of NGC 1068 is taken as 1148 km s^{-1} (Brinks et al. 1997), and the distance 14.4 Mpc (Bland-Hawthorn et al. 1997) where 1" corresponds to 70 pc.

2. Archival Data

2.1. Data

We use the data for NGC 1068 from the HST archive, taken by Cecil et al. (2002) with HST/STIS using the medium-resolution grating G430M centered at [O III] and Hβ line
wavelengths (Table 1). They were taken at six slit positions as shown in Figure 1. The data at the fifth slit position were taken redundantly, and the two sets were used to spatially align the data taken a year apart. The slit width was set to be 0\".2, and the resulting spectral resolution at \sim5000 Å is \sim5000, corresponding to a kinematic resolution of 60 km s\(^{-1}\) (STIS Instrument Handbook, chapter 13). Since on-chip binning was done, the spectral sampling of the data is \sim0.55 Å per pixel. The spatial sampling is 0\".051 per pixel (while the HST’s spatial resolution at \sim5000 Å is \sim0\".05).

### Table 1

| Name          | Observing Date | Grating | Spectral Range (Å) | Position |
|---------------|----------------|---------|--------------------|----------|
| o56502010     | 1999 Oct 2     | G43M    | 4818–5104          | 1        |
| o56502020     | 1999 Oct 2     | G43M    | 4818–5104          | 2        |
| o56502030     | 1999 Oct 2     | G43M    | 4818–5104          | 3        |
| o56502040     | 1999 Oct 2     | G43M    | 4818–5104          | 4        |
| o56502050     | 1999 Oct 2     | G43M    | 4818–5104          | 5        |
| o56503010     | 2000 Sep 22    | G43M    | 4818–5104          | 5'       |
| o56503020     | 2000 Sep 22    | G43M    | 4818–5104          | 6        |

2.2. Processing

The data have been cosmic-ray-rejected first by the HST pipeline and then by using la-cosmic (van Dokkum 2001). The remaining hot pixels and negative pixels were filled with the median of adjacent pixels. The rest of the processing steps in the pipeline have been implemented using stistools (ver. 1.1). Then, a linear continuum was subtracted using the continuum windows at both sides of the [O III] \(\lambda\lambda4959, 5007\) line wavelengths. Then the contribution of the [O III] \(\lambda4959\) line was removed by shifting and scaling the [O III] \(\lambda5007\) line.

We have extracted the data over the velocity range of \pm2500 km s\(^{-1}\) of the [O III] \(\lambda5007\) line centered at the systemic velocity of NGC 1068. The resulting six 2D spectra are shown in Figure 2. These six slit data were assembled to form a data cube of the 2D spatial axes and wavelength axis. Then we interpolated the data cube along the direction perpendicular to the slit direction, in order to have a matched spatial sampling in the two spatial directions (0\".05 × 0\".05).

The origin of the spatial coordinates is taken to be the supposed position of the central black hole. This position has been determined as the center of the centro-symmetric polarization pattern in the HST image (Cecil et al. 1995; Kishimoto 1999), and it is about 0\".1 south of the UV/optical continuum peak (see Table 2 in Kishimoto 1999 for details). Below we focus on the central region of \pm2\" along the slit direction (see more below about this limit).

### 3. Velocity Inversion Mapping of the 3D Flux Distribution

3.1. 3D Mapping

In this section, we describe how we reconstruct the 3D flux distribution from the resolved emission-line spectra, or radial velocities of the line-emitting gas clouds. We would need a few assumptions on the cloud velocities around the nucleus: (1) velocity vector \(\mathbf{v}\) is parallel to the position vector \(\mathbf{r}\) with respect to the nucleus (\(\mathbf{r} \parallel \mathbf{r}\)); (2) the velocity amplitude \(v\) is determined as a certain function \(f\) of the distance \(r\) from the nucleus, i.e., \(v = f(r)\). We also assume that we know the position of the nucleus projected on the sky plane, which we designate as the \(x\)-\(y\) plane (see Figure 3). This is not necessarily the case for Type 2 AGNs, but we do know the nucleus position of NGC 1068 quite accurately thanks to the HST imaging polarimetry data.

If we have high-spatial-resolution integral field spectroscopic data of the line-emitting gas in the nuclear region, the observables for each line of sight are the line flux as a function of the radial velocity \(v_r\) and the projected distance \(r_{proj}\) from the nucleus for that line of sight. The two quantities, \(v_r\) and \(r_{proj}\), are related to the distance \(z\) of the line-emitting material from the

![Figure 1. Slit positions of STIS observations for NGC 1068 (Cecil et al. 2002) overlaid on the HST/FOC [O III] image in grayscale (Macchetto et al. 1994). The STIS slit direction was at 38\" east of north. The position of the hidden nucleus is indicated as a plus sign.](image1)

![Figure 2. HST/STIS 2D spectra at six slit positions as indicated in Figure 1 with the corresponding position number. The horizontal axis is the dispersion direction, while the vertical axis is along the spatial direction.](image2)
are calculated in the same way, so that we
s
s
s
2
vr
analysis below is not affected by the detailed value of
k
Nevertheless, we can determine
cloud, used in the velocity inversion process for reconstructing the 3D
Thus the
vk z r
5
Figure 3. Illustration of the variables and observables of a spatially resolved
cloud, used in the velocity inversion process for reconstructing the 3D
distribution.
sky plane as

\[ v_r = f(r) \frac{z}{r} \]  

(1)

where

\[ r = \sqrt{r_{\text{proj}}^2 + z^2}. \]  

(2)

Therefore, in principle, we can convert \( v_r \) to \( z \) for each line of
sight, i.e., invert the observed radial velocity to the 3D position of
the gas. In practice we might not have a unique solution of \( z \)
for a given \( v_r \) and \( r_{\text{proj}} \), depending on the exact form of the
velocity function \( f(r) \). However, the inner velocity field has
been inferred to have quite a simple form (Crenshaw & Kraemer 2000; Das et al. 2006):

\[ v = f(r) = kr. \]  

(3)

In this case, we simply have

\[ v_r = k z. \]  

(4)

Thus the flux distribution in \( xxv_r \) 3D space becomes equivalent
to that in \( xyz \) 3D space. A more general power-law form

\[ v = f(r) = kr^{\alpha} \]  

(5)

has also been investigated (Das et al. 2006). In this case, we have

\[ v_r = k z (r_{\text{proj}}^2 + z^2)^{\alpha-1/2}. \]  

(6)

As long as the right-hand side is a monotonic function of \( z \), we
can simply invert \( v_r \) to obtain \( z \). Below we restrict the inversion
mapping to the inner region, where the velocity field seems
apparently linear, or the “accelerating region” as designated by
Das et al. (2006), which is about \( \pm 2^\circ \) along the slit from
the nucleus, and implement this inversion process in this
region only.

3.2. Determination of the Constant \( k \)

The mapping above does not specify the free parameter \( k \),
which sets the scale in the \( z \)-direction with respect to that in
the \( x-y \) plane. Its approximate value can easily be obtained as
\( v_r/r_{\text{proj}} \). Since this is only a scaling in one direction, our
analysis below is not affected by the detailed value of \( k \).
Nevertheless, we can determine \( k \) in a relatively robust way.

A reasonable assumption would be that our line of sight is
not special—the spread of the flux distribution in the \( z \)-
direction is similar to that in the \( x-y \) plane. Here we propose to
calculate \( k \) from \( \sigma_v = k \sigma_r \), where \( \sigma_r \) is given as

\[ \sigma_z^2 = \frac{\sigma_r^2 + \sigma_y^2}{2}. \]  

(7)

Here each \( \sigma \) denotes the flux-weighted dispersion in each axis
direction. This dispersion is calculated from

\[ \sigma_r^2 = \frac{\sum (x - \bar{x})^2 \cdot F_{\text{OIII}}(x, y, v_r)}{\sum F_{\text{OIII}}(x, y, v_r)} \]  

(8)

and

\[ \bar{x} = \frac{\sum x \cdot F_{\text{OIII}}(x, y, v_r)}{\sum F_{\text{OIII}}(x, y, v_r)}. \]  

(9)

where \( F_{\text{OIII}} \) is the [O III] \( \lambda 5007 \) line flux distribution in \( x-y \)
and the summation is taken over this space. The dispersions \( \sigma_r \) and \( \sigma_y \) are calculated in the same way, so that we
can determine the constant \( k \).

As for the uncertainty of \( k \), we would postulate that \( \sigma_r^2 \) could
be as large as \( \sigma_r^2 + \sigma_y^2 \), and at minimum it would be equal to \( \sigma_r^2 \)
or \( \sigma_y^2 \), whichever is smaller. Thus, \( \sigma_z^2 \) as determined by the
above Equation (7) would have an uncertainty of roughly a factor
of 2. Therefore, \( \sigma_z \) and thus \( k \), would have an uncertainty
of roughly a factor of \( \sqrt{2} \).

4. Reconstructed 3D View of the Nuclear Region

In Figure 4, we show the results of this 3D reconstruction
for the case of a linear velocity field, \( v = kr \), using the
visualization software \textit{Mayavi} (Ramachandran & Varoquaux 2011). As described in the previous section, for this linear
velocity field, the “reconstructed” 3D distribution is essentially
the original \( xxv_r \) data cube of the [O III] \( \lambda 5007 \) line in shape
(after subtraction of the continuum and removal of the [O III] \( \lambda 4959 \) line), except for the scaling in the \( v_r \) direction. The 3D
flux distribution is shown in a volumetric visualization in the
left panel, while two slices of the same distribution, passing
through the position of the nucleus (i.e., the black hole optically
hidden from direct view) indicated by a black dot, are shown in
the right panel. We also show further sets of 2D cuts in
Figure 5.

We have determined the constant \( k \) to have a dispersion of the
flux distribution in the \( z \)-direction the same as that in the
sky plane, as described in Section 3.2, where the resulting value of \( k \) was \( 1.04 \times 10^3 \) \( \text{km s}^{-1} \) \( \text{arcsec}^{-1} \), or 14.8 \( \text{km s}^{-1} \) \( \text{pc}^{-1} \), for
this data set. There is remaining uncertainty in \( k \), but we note
again that a different \( k \) would only scale the 3D distribution in
the \( z \)-direction (with respect to the sky plane; Figure 3). The
remaining uncertainty in \( k \) would not leave considerable
uncertainty in the overall 3D shape.

A few clouds, particularly cloud B in the notation of Evans et al. (1991), which is just north of the nucleus, have a shape
quite spread in the \( z \)-direction. This is due to the large velocity
dispersion of the gas in these clouds. The velocity inversion
mapping adopted here would not differentiate radial velocities
from velocity dispersions, hence a large velocity dispersion
produces an artifact on the 3D distribution. However, the
velocity dispersions in most of the clouds seem to be of the
same order as, or less than, the volumetric spread over the \( x-y \)
plane, and this issue does not affect the overall reconstructed
distribution.

While somewhat messy, the distribution is certainly biconical in 3D, with the southern side rather extinct perhaps
due to the absorption by the host galaxy disk. Even more
importantly, the conical distribution seems roughly hollow.
This is all consistent with the model proposed by Das et al.
(2006) and Crenshaw & Kraemer (2000) originally. Here we
show this distribution in 3D directly from the data. We further
discuss the implications of this outflowing, hollow structure in
Section 5.

In Figure 6, we show the 3D distribution reconstructed with
different power-law indices of the velocity field. The detailed
shape changes, of course, but the overall distribution is not so
sensitive to the choice of the index. Furthermore, we argue in
Section 5 that the linear velocity distribution (i.e., the $\alpha = 1$
case) has more physical background and motivation.

5. Discussion

5.1. Comparison with Previous Modelling

The biconical hollow geometry in outflow for NGC 1068 at
this 100 pc scale has been adopted and investigated in detail by
Das et al. (2006). The outflow geometry was originally
proposed by Crenshaw & Kraemer (2000) based on the
HST/STIS single long-slit data as well as the conical
morphology seen in earlier imaging data including HST images
(Evans et al. 1991; Macchetto et al. 1994). The single long-slit
data showed mainly two separate velocity components at each
spatial location along the slit, and it has been argued that the
data are well explained if the biconical hollow geometry and
the linear velocity field ($v = kr$) are both assumed. The latter
assumption originates from the radial velocity being seemingly
proportional to the projected distance from the nucleus. The
multi-slit data have strengthened this idea, and Das et al. (2006)
have modeled the data based on this biconical hollow geometry
and determined a few critical model parameters.

Our approach here is that, if we assume this linear velocity
field, we can actually invert the radial velocity data to derive
and reconstruct directly the 3D distribution of the line-emitting
material. The only parameter we have to determine is the
proportionality constant $k$, but this has only a scaling effect in
one direction. We determined it to have the distribution “round,” i.e.,
having roughly the same spatial extent when viewed from different directions. This assumption approxi-
ately corresponds to the modeling by Das et al. (2006) where
the distribution is set to be axisymmetric. In fact, they obtained
from the fit the value of the constant $k$ in the linear velocity law
be 14.3 km s$^{-1}$pc$^{-1}$ (2000 km s$^{-1}$ per 140 pc; from Table 2
in Das et al. 2006), while we deduced essentially the same
value (14.8 km s$^{-1}$pc$^{-1}$; Section 4). Our results support
the overall biconical, hollow geometry proposed by Crenshaw &
Kraemer (2000) and Das et al. (2006), thus confirming their
modeling results. The reconstructed 3D distribution could give
even more details and show the deviation from the simple
geometry. However, we have to keep in mind that the
reconstruction is based on the assumption of the velocity field,
which we discuss in the next section.

5.2. Physical Interpretation of the Velocity Field

Detailed investigations have been done on the interpretation of
the seemingly linear velocity field (Das et al. 2007). We
could interpret the field as a given gas cloud being accelerated
along the radial track from the nucleus. For a cloud with a
given mass, a constant force (acceleration) would result in
the cloud’s velocity $v \propto r^{1/2}$ where $r$ is the distance from
the nucleus. The case of the linear velocity $v \propto r$ would mean
that the force $F$ is increasing in proportion to $r$ ($F \propto r$). If this
accelerating force is the radiation pressure on dust grains, we
would have to expand the cross section $S$ of the blob, keeping

Figure 4. Reconstructed distribution of the [O III] line flux in 3D, assuming the linear velocity field $v = kr$ (where $k$ is $1.04 \times 10^4$ km s$^{-1}$ arcsec$^{-1}$ or 14.8 km s$^{-1}$ pc$^{-1}$; see text). The position of the black hole is indicated as a black point at the center. The reconstructed box scale is 1.5/2 × 4", or ~84 pc × 280 pc, parallel to the sky plane, and 280 pc along the line of sight. The HST/FOC O III image is shown for reference as the 2D flux distribution projected on to the sky plane.
the whole blob still UV–optically thick, (1) with $S \propto r^2$ to keep the force constant, or (2) with $S \propto r^3$ to have $F \propto r$. Das et al. (2007) have investigated different cases of effective acceleration, concluding that the observed gradual acceleration of $v \propto r$ is quite difficult to achieve. Rather, the acceleration is quite possible on the innermost scale, and the cloud would keep the same speed over large distances in the absence of a significant drag force from the ambient medium.

5.3. “AGN Big Bang”—Episodic Acceleration

Another way of interpreting this linear velocity field is that each cloud is actually moving at its own constant speed. All the clouds were accelerated in the innermost region, and are moving away from the nucleus at constant velocities, like the Hubble expansion. Das et al. (2007) noted the velocity field as Hubble-flow-like, and this Hubble-flow interpretation has been advocated by Ozaki (2009). In this case, the clouds are interpreted to have a constant velocity over the dynamical time $t_{\text{dyn}}$ of $\sim r/v = 1/k$. This would mean that an episodic acceleration, or an “AGN Big Bang,” has occurred at the nucleus a time of $1/k$ ago. Since we have $k \sim 15 \text{ km s}^{-1} \text{ pc}^{-1}$ for this inner region of NGC 1068, the timescale $t_{\text{dyn}}$ would roughly be $\sim 0.7 \times 10^5 \text{ yr}$.

This explanation of the linear velocity field would give credence to the 3D-reconstructed distribution assuming $v \propto r$, and not the other power-law forms. In addition, this
interpretation would be valid only in the region within a certain radius where the velocity could be kept approximately constant for a given cloud without a significant cause of deceleration. We have limited our analysis to the region within 2" from the nucleus where the radial velocity seems proportional to the projected distance (see Figure 2; called the “accelerating region” by Das et al. 2006). For the region outside, we would need a further consideration, but the clouds there could belong to a different episode of acceleration, further in the past.

Wang et al. (2010) identified an extended soft X-ray emission in NGC 4151 at \(10^4\) light-years (a few kiloparsecs) from the nucleus. Based on its high surface brightness, they infer that this could be due to an episodic outburst of the nucleus that occurred \(10^4 – 10^5\) yr ago. NGC 4151 has an NLR-scale outflow, spatially and spectrally resolved by HST (Das et al. 2005), that is very similar to the outflow we discuss here, while NGC 1068 does not seem to show such a large-scale extended X-ray emission beyond kiloparsec scale (Ogle et al. 2003; Kallman et al. 2014). It would be interesting to study different AGNs with spatially resolved inner-NLR outflows systematically, in light of the scenario where the outflow is from an episodic outburst and in the resulting Big-Bang-like velocity field. In this scenario, the estimation of the event timescale is relatively robust (the uncertainty corresponds to that in \(k\), and thus would roughly be a factor of \(\sqrt{2}\), and the timescale might be correlated with the characteristics of the objects. We aim to implement these studies elsewhere.

5.4. Comparison with the Interferometrically Resolved Inner Structure

It is quite instructive to compare the conical and hollow 3D distribution at this 100 pc scale with the structure observed for an inner region at a parsec scale. We summarize four important observational aspects below, and discuss their implications in the next section.

(1) First, recent IR interferometry has shown that the mid-IR emission at the inner parsec scale, or tens of dust sublimation radii \(R_{\text{sub}}\), is polar elongated, rather than equatorially elongated (Hönig et al. 2012, 2013; Tristram et al. 2014; López-Gonzaga et al. 2014, 2016). Therefore the inner parsec-scale structure is extended toward the conical and hollow distribution in the NLR at an arcsecond or 100 pc scale that we discuss here. A mid-IR polar elongation is seen in many nearby AGNs with subarcsecond mid-IR imaging (Asmus et al. 2016).

(2) On the other hand, when the effective resolution is high enough to resolve even an inner scale of several \(R_{\text{sub}}\) in the mid-IR, which is the case for the two Type 2 objects NGC 1068 and Circinus galaxy, we see an equatorially elongated structure, in addition to the outer polar structure discussed in (1) above (López-Gonzaga et al. 2014; Tristram et al. 2014).

(3) Quite importantly, the measured size and flux indicate a mid-IR emissivity of sub-unity, i.e., \(\sim 0.1 – 1\). We summarize this in Figure 7. The flux and the size of the emitting region measured at a certain wavelength give us an estimation of the surface brightness. With a further estimation of the color temperature from the spectral shape, we can estimate the emissivity, i.e., the ratio of the surface brightness of the region to that of blackbody emission at that temperature. The three red filled squares in Figure 7 are the mid-IR interferometric measurements for NGC 1068, modeled with three Gaussian components, each giving a set of size, flux, and temperature (López-Gonzaga et al. 2014). We also collected mid-IR interferometric size measurements with temperature estimation in the literature, as well as similar near-IR interferometric measurements, all shown as filled circles in Figure 7 (Kishimoto et al. 2011a, 2011b; Burtscher et al. 2013; GRAVITY Collaboration et al. 2020a). The data are plotted on grids of graybody surface brightness as a function of temperature with emissivities from 1 (i.e., blackbody) to 0.001 at 12 \(\mu\)m (red) and 2.2 \(\mu\)m (blue). The data points indicate that the nuclear IR emission is quite close to the blackbody surface brightness—some of the 12 \(\mu\)m points are above the blackbody

Figure 6. Comparison of the reconstructed 3D distribution using different power-law indices in the velocity law. All representations are viewed from the +x-axis direction, parallel to the sky plane.
curve, which means that the temperature of the emitting material is probably somewhat higher than the color temperature. But in any case, the emissivity is all sub-unity.

(4) In comparison to these emissivity estimates for the inner parsec-scale structure, we can estimate the emissivity of the 100 pc scale HST-resolved clouds in NGC 1068 using the resolved mid-IR flux of the clouds as quantified by Bock et al. (2000). They measured the spatially resolved mid-IR spectral energy distribution for five different clouds of 0"2 diameter, corresponding to the notation of Evans et al. (1991) to the clouds A/B, C/E, D, F, and the clouds just south of the nucleus. These five measurements are indicated accordingly in Figure 7 with open squares. The emissivity of these discrete clouds is ~0.001—0.01, much lower than that of the inner structure in general, and strikingly, the loci of these clouds on Figure 7 look quite continuous from the interferometrically resolved structure. Therefore these two structures should be closely connected, as we discuss in the next section.

5.5. Obscuration with Outflow: “Flaring Windy Torus”

The emissivity of sub-unity found for the inner parsec-scale structure is in fact the value expected for the surface of the UV–optically thick clouds directly illuminated by the nucleus and observed in the IR (see, e.g., Figure 3 of Hönig & Kishimoto 2010). This implies that these inner (interferometrically resolved) polar clouds at a parsec scale are participating in the obscuration of the nucleus, i.e., they must be a part of the AGN “torus.” Then, to avoid polar obscuration (to have the Type 1 line of sight clear), we would need to distribute these UV–optically thick clouds in a hollow geometry, and likely in a flaring configuration in order to have each cloud directly illuminated by the nucleus. For the case of NGC 1068, we indicate in Figure 8(a) the approximate spatial scale discussed here as the inner box of side 0"1, corresponding to ~7 pc. This is a region of ~30 $R_{	ext{out}}$ in radius. The schematic 3D illustration of the distribution of the ionized gas and high-temperature dust ($>300$ K) inferred here for this inner region is shown in Figure 8(b), with a 2D cut shown in Figures 8(c) and (d). This is quite similar to the configuration described by Höning & Kishimoto (2017) and Höning (2019), but the flaring geometry proposed here has both the inner equatorial elongation and outer polar elongation in a single component.

The conical and hollow 100 pc scale distribution, 3D-reconstructed here, would give further support for the inferred inner structure illustrated in Figures 8(b)–(d), which is also conical and hollow. We would infer that these two structures are smoothly connected, which is consistent with the continuous distribution in emissivity in Figure 7. The inferred flaring configuration is also consistent with the outer polar and inner equatorial elongation (combination of points (1) and (2) in Section 5.4).

The inferred hollow/flaring inner geometry does not directly have any kinematic information yet. However, since the 100 pc scale outflow is very likely to be connected to this inner parsec-scale structure, the inner one must be in outflow as well. We would then suggest that the AGN “torus,” the obscuring structure, would indeed be the inner part of this hollow conical outflow. Thus it is an obscuring and outflowing structure. The HST-resolved high-velocity clouds would probably be the outer part of this flaring windy torus, expanded at large distances from the nucleus and become optically thin, consistent with the mid-IR emissivity of 0.01–0.001 (point (4) in Section 5.4).

The inferred inner geometry could actually be consistent with the reconstructed image of the parsec-scale region of NGC 1068, which has recently been obtained with VLTI/GRAVITY in the near-IR (GRAVITY Collaboration et al. 2020b). However, the comparison might not be straightforward due to the possible significant extinction in the near-IR for this Type 2 object.

5.6. Relations to Models and Submillimeter Observations

This observational picture seems consistent with the theoretical outflow models developed by, e.g., Königl & Kartje (1994) and Wada (2012, 2015), which posit the inner part of the outflow as the obscuring structure. Here we argued that such a conical, hollow outflow is observationally seen (i.e., can be reconstructed) at ~100 pc scale, and can be well inferred at ~pc scale as its inward extension based on the IR interferometric observations.

This structure traced by the ionized gas and high-temperature dust grains probably has quite a good correspondence to that traced by molecular gas observed in submillimeter high-resolution maps for NGC 1068. In the inner UV–optically thick part of the outflow, the illuminated “bright” side has ionized gas and high-temperature dust, whereas the shadowed, “dark” side of each of these clouds has molecular gas and low-temperature dust (see Table 2 for a summary).

ALMA has now the resolution to spatially resolve the dark side of the hollow conical distribution (Figure 8(d)), and we do see an apparently corresponding, X-shaped morphology in submillimeter molecular lines and continuum: CO ($J = 6−5$) at 4 pc (0"06) resolution (García-Burillo et al. 2016); 256 GHz
continuum at 1.4 pc (0\''01) resolution (Impellizzeri et al. 2019); HCO\(^+\) (4–3) at 2 pc (0\''03) resolution (García-Burillo et al. 2019). The spatial distribution of the high-velocity CO (6–5) line-emission peaks (Gallimore et al. 2016) could also correspond to the dark sides of the outflow clouds. A part of HCN (3–2) line emission and absorption also shows outflow features in radial velocities at a high enough spatial resolution (Impellizzeri et al. 2019). We also note that outflow velocities of these molecular gases (~100 km s\(^{-1}\)) seem roughly consistent with the inward extension of the linear velocity law discussed here (e.g., 75 km s\(^{-1}\) at 5 pc for \(k = 15\) km s\(^{-1}\) pc\(^{-1}\); Section 4).

One complication at submillimeter wavelengths seems to be that we observe both an outflow and a rotating gas (Imanishi et al. 2018; García-Burillo et al. 2019; Impellizzeri et al. 2019)—the latter is likely in the equatorial plane and perhaps fueling the nucleus, thus could be called a “fueling disk” component (Table 2). Disentangling the two has seen substantial progress with better spatial resolutions. As discussed by Höning (2019), the results of high-angular-resolution observations in the infrared and submillimeter regions can be understood in a unifying way if we take into account the two-component nature of the submillimeter-emitting material.

### 6. Summary and Conclusions

Two-dimensional spectral imaging data have become quite abundant in recent years. We have shown that the 2D radial velocity map from such data directly gives us the distribution of emission-line flux in 3D space, if we assume a certain velocity field. We used archival HST/STIS multi-slit data for the prototypical Seyfert 2 galaxy NGC 1068, and reconstructed the 3D distribution of the line flux directly from the high-spatial-resolution velocity map.
Among various velocity laws, the linear velocity field can in principle be physically understood with the scenario in which all the clouds were accelerated simultaneously on a very short timescale in the innermost region. The clouds have been moving away from the nucleus with a constant speed, leading to the radial distance of each cloud from the nucleus being proportional to the velocity of that cloud. This “AGN Big Bang” event, inferred to have occurred \( \sim 10^5 \) yr ago, could be an episodic one in the history of the object.

The 3D distribution of the emission-line flux reconstructed with this linear velocity law shows a roughly hollow biconical structure at a 100 pc scale. Combined with the recent IR interferometric parsec-scale results, we infer that this hollow structure at a 100 pc scale. Combined with the recent IR interferometric parsec-scale results, we infer that this hollow structure at a 100 pc scale. Since the emissivity of the inner parsec-scale conical outflow extends from the inner parsec scale to the 100 pc scale. The outflow, or the instant acceleration in the innermost region, might have been caused by the radiation pressure on dust grains. If the illuminating radiation is anisotropic, being strong in the polar direction, the observed polar hollow structure might originate from such anisotropic radiation from the nucleus. In fact, such anisotropy could in principle be constrained from the 3D distribution obtained here. We plan to apply our analysis to many other AGNs with high-spatial-resolution velocity maps in a future publication.

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