The AGN Ionization Cones of NGC 5728. I. Excitation and Nuclear Structure

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Abstract

We explore the gas morphology and excitation mechanisms of the ionization cones of the Type II Seyfert galaxy NGC 5728. Near-IR and optical data from the SINFONI and MUSE integral field units on the Very Large Telescope are combined with Hubble Space Telescope optical images, Chandra X-ray data, and Very Large Array radio observations. The complex nuclear structure has a star-forming (SF) ring with a diameter of 2 kpc. A radio jet impacts on the interstellar medium at about 200 pc from the nucleus, with the supernova remnants in the SF ring also present. Emission-line ratios of [Fe II] and H II show heavy extinction toward the nucleus, moderate extinction in the SF ring, and reduced extinction in the ionization cones. The active galactic nucleus (AGN) is hidden by a dust bar with up to 19 mag of visual extinction; the dust temperature at the nuclear position is ~870 K. An X-ray jet is aligned with the ionization cones and associated with high-excitation emission lines of [Si VI] in a coronal line region extending 300 pc from the nucleus. Molecular hydrogen is spatially independent of the cones, concentrated in a disk equatorial to the SF ring, but also showing entrainment along the sides of the bicone. Gas masses for warm and cold H₂, H I, and H II are estimated, and the excitation mechanisms for ionized and molecular gas are elucidated, from both optical (which shows a clean SF–AGN mixing sequence) and infrared diagnostics (which show more complicated, multicomponent excitation regimes).

Key words: galaxies: active – galaxies: individual (NGC 5728) – galaxies: nuclei – galaxies: Seyfert – galaxies: structure – ISM: jets and outflows

1. Introduction

The unified model of active galactic nuclei (AGNs) predicts that radiation from the accretion disk around the supermassive black hole (SMBH) is collimated by a torus of obscuring dust and gas, which is broadly symmetric around the accretion flow axis. This radiation impinges on the interstellar medium (ISM), exciting the gas by photoionization and transferring mechanical energy to the gas by radiation pressure and disk winds; this appears in the form of cones extending from the nucleus. These cones are observed in local Seyfert galaxies and are more frequently seen in type II (obscured) Seyferts than type I (unobscured) Seyferts (Schmitt & Kinney 1996), consistent with unification. The kinematics and excitation of the gas in these cones are of interest to elucidate excitation mechanisms, to examine the interaction of the AGN with its host galaxy, and to correlate optical and infrared observations with radio and X-ray.

Urry & Padovani (1995), in the seminal review paper on AGN unification, cited NGC 5728 as the paradigm of a type II AGN with these ionization cones. This makes it a prime target for investigation, particularly using observations in the near-IR (NIR), allowing penetration of obscuring dust. In the present paper (“Paper I”), we will explore in detail the nuclear structure of this galaxy at multiple wavelengths and characterize the narrow-line region (NLR) gas morphology and excitation. In the companion paper (M. Durré & J. Mould 2018, in preparation, hereafter “Paper II”), we will use these data to explore the kinematics of the cones, showing that they are AGN-driven outflows, determining mass outflow rates and power, and relating these to the AGN bolometric luminosity and the amount of gas that can be expelled during the AGN activity cycle; the SMBH attributes are also derived. We will also determine the stellar kinematics and relate them to the gas kinematics.

The basic parameters for NGC 5728 are given in Table 1. Apart from the AGN activity, the nucleus has a highly complex structure. The Spitzer Survey of Stellar Structure in Galaxies (S4G; Buta et al. 2015) lists the morphology as (R)SBq 1 lb, lr, nb)0/a, which indicates a barred spiral with a closed outer ring, an inner pseudo-ring/lens, and a nuclear ring and bar/bar-lens. This morphology is important in the context of star formation in the nuclear region.

From the Two Micron All Sky Survey (2MASS) H-band absolute magnitude with a mass-to-light ratio of 1 at H and a solar absolute magnitude of $M_H = 3.3$ (Binney & Merrifield 1998), the estimated galaxy mass is $7.2 \times 10^{10} M_\odot$.

The Carnegie-Irvine Galaxy Survey (Ho et al. 2011) image (Figure 1) clearly shows the outer ring with faint trailing spiral arms. The bar is weak, with the region between the nucleus and the outer ring being reasonably smooth with some faint dust rings. Rubin (1980), using Hα emission line measurements, found that the rotation curve along the NE–SW axis was flat and that the NE axis was approaching; that study concluded that the near side was to the NW, based on the trailing faint spiral arms. She also deduced that the noncircular velocities could be modeled equally well by an additional axisymmetric expansion, or by a displaced inner disk or spheroidal/triaxial inner bulge. NGC 5728 has ionization cones that are oriented across our line of sight (LOS). Gorkom (1982) first observed asymmetrical optical and radio emissions from this galaxy; their Very Large Array (VLA) 6 and 20 cm observations showed a diffuse $10^6$ region that was coextensive with the optical emission, with a compact nucleus and jet. These observations were followed up by Schommer et al. (1988); they concluded that the gas was streaming inward; however, their data did not exclude outward motions, as suggested by the double-peaked Hα emission line region near the nucleus. Arribas & Mediavilla (1993) noted that the kinematic center of the Hα, [N II], and [S II] emission lines and the radio flux did not coincide with the emission-line flux maximum, suggesting that the nucleus was highly obscured. The Hα+[N II] and [O III] emission line images from the Hubble Space
**Telescope (HST)** observations of Wilson et al. (1993) revealed a spectacular biconical structure with an overall extent of 1.8 kpc.

**HST** UV polarimetry of the nucleus (Capetti et al. 1996), using the Faint Object Camera, revealed a centrosymmetric pattern of scattered light originating in the hidden nucleus; the polarization upper limit was 1.9%, in line with ground-based observations. This showed that the cones were much wider than that inferred from the emission lines (55°–65°), implying that some of the torus is transparent to UV light while still blocking the ionizing radiation. The cone symmetry was used to locate the nucleus behind a dust lane. The activity type is classified as Seyfert 1.9 (Véron-Cetty & Véron 2006), based on broad Hα Balmer line visibility.

The kinematics and excitation mechanisms of H2 and [Fe II] lines in a sample of active galaxies were studied in Rodríguez-Ardila et al. (2004a, 2005), which included this galaxy, using long-slit observations from the 0.8–2.4 μm IRTF Spex spectrograph. They showed that, in general, the H2 was kinematically decoupled from the NLR, with this particular galaxy having the highest ratio of H2 to Brγ flux in their sample of 22 AGNs. They estimated a warm H2 mass of ~900 M⊙ in the nucleus. Rodríguez-Ardila et al. (2011) also detected the coronal line (CL) of [Si VI]; however, they did not observe any CLs in this object with an ionization potential (IP) >167 eV, indicating a limit to the hard X-ray flux. From WiFeS optical integral field unit (IFU) observations, Dopita et al. (2015) reported that the NLR was much more extended than from Wilson et al. (1993): 4.4 kpc rather than 1.8 kpc in extent. Using the spectra for this object from Rodríguez-Ardila et al. (2004a), which were taken with a 0″8 x 15″ slit, Riffel et al. (2009) deduced a mixture of 70% intermediate-age (100 Myr–2 Gyr) and 30% old (>2 Gyr) stellar population contributions to the continuum, with corresponding mass fractions of 25% and 75%, with no blackbody dust component.

In this paper, we use the standard cosmology of H₀ = 73 km s⁻¹ Mpc⁻¹, ΩMatter = 0.27, and ΩVacuum = 0.73. All images are oriented so that north is up, east is left.

### Table 1: NGC 5728 Basic Parameters

| Parameter          | Value                      | Reference                  |
|--------------------|----------------------------|----------------------------|
| R.A.               | 14°42′23″+9                | Mould et al. (2000)        |
| Decl.              | −17°15′11″                 |                            |
| Distance           | 41.1 ± 2.9 Mpc            |                            |
| Scale              | 200 pc arcsec⁻¹           |                            |
| z                  | 0.009353                  | Catinella et al. (2005)    |
| Morphology         | SAB(r)z                   | de Vaucouleurs et al. (1991)|
| Activity           | Sy 2 (Sy 1.9)             | Véron-Cetty & Véron (2006) |
| M_B (2MASS)        | −23.85                    | Skrutskie et al. (2006)    |

Note.  

* Virgo+GA+Shapley flow-corrected distance, H₀ = 73 km s⁻¹ Mpc⁻¹

### Figure 1

![Figure 1. NGC 5728 star-cleaned color-composite image from CGS, created from the B, V, and I images and cleaned of stars, as described in Ho et al. (2011). The image is oriented north up, east left. The sides of the image are 4.6, equivalent to 55 kpc at the distance of NGC 5728. The features visible are the outer ring, faint arms trailing from SF peaks at the end of the major bar, a smooth disk with dust lanes, and the complex inner nuclear structure, composed of a ring with a bar. The dotted line indicates the morphological axis and kinematic line of nodes, and the arrows indicate the rotation direction. The near and far sides of the galaxy are labeled.](http://www.eso.org/sci/software/gasgano.html)

### 2. Observations, Data Reduction, and Calibration

We obtained NIR IFU data from SINFONI on VLT-U4 (Yepun), both from our own observations (J-band filter) and from the MPE group (H+K-band filter), who kindly let us use the data from their LLAMA (Luminous Local AGN with Matched Analogues) survey (Davies et al. 2015). Each data set consists of two object frames, combined with a sky frame with the same exposure, in the observing mode “Object-Sky-Object.” For the J-band SINFONI observations, the offset was 30″ in decl., plus a 0″05 jittering procedure; the offset for the H+K observations was 60″ in R.A., plus a 0″1 jitter. Standard stars are observed close to the observation at a similar air mass.

We also obtained archival data at optical wavelengths from the MUSE optical IFU instrument (Bacon et al. 2010) on the ESO VLT for the TIMER (“Time Inference with MUSE in Extragalactic Rings”) survey (Gadotti et al. 2018); these data were reduced before archival release and are used with the kind permission of Dr. Gadotti.

Our observations are summarized in Table 2, which also includes the details of the MUSE TIMER program optical observations.

The SINFONI data reduction was performed using the recommendations from the ESO SINFONI data reduction cookbook and the gasgano (ESO 2012) software pipeline (version 2.4.8). Bad read lines are cleaned from the raw frames using the routine provided in the cookbook. Calibration frames are reduced to produce nonlinearity bad pixel maps, dark and flat fields, distortion maps, and wavelength calibrations. Sky frames are subtracted from object frames, corrected for flat field and dead/hot pixels, interpolated to linear wavelength and spatial scales, and resampled to a wavelength-calibrated cube, at the required spatial scale. The sequence of reduced object cubes are mosaicked and combined to produce a single data cube. Subsequent cube manipulation and computation are done using the cube data viewer and analysis application QFitsView (Ott 2012), which incorporates the DPUSER language.
Notes.

a Exposure time (s) for each on-target frame.
b Seeing from the ESO Paranal Astronomical Site Monitoring (VLT) or the Maunakea Weather Center DIMM archive (Keck).
c Measured spectral resolution.
d Observed field of view.
e SINFONI plate scale is rebinned to half size in the final data cube.
f Barycenter correction in km s$^{-1}$ from “Barycentric Velocity Correction” website http://astrutils.astronomy.ohio-state.edu/exofast/barycorr.html (Wright & Eastman 2014).
g Spectral velocity resolution (km s$^{-1}$)
h Spatial resolution.
i Data not available.

Standard stars are used for both telluric correction and flux calibration; these had the spectral types of B2 to B9, which only have hydrogen and helium lines in their spectra. Flux calibration is done by extracting the stellar spectrum from the data cube within an aperture, chosen using logarithmic scaling on the collapsed “white-light” image. A segment of the spectrum is chosen that avoids telluric features and stellar absorption lines, on or near the effective wavelength for the filter. The total counts in a 10 nm window centered on the chosen wavelength are divided by the exposure time and the window wavelength width to get a value of counts s$^{-1}$ nm$^{-1}$. This is equated to the stellar magnitude found from the 2MASS catalog (Skrutskie et al. 2006, through the SIMBAD astronomical database$^2$), converted to a flux density using the website “Conversion from magnitudes to flux, or vice-versa.”$^3$ The telluric correction spectrum was created from the standard-star spectrum by manually fitting and removing the hydrogen and helium absorption features and then dividing by a blackbody spectrum of the correct temperature for the spectral type. This spectrum is normalized and is divided into each spectral element. This temperature is somewhat higher than given in standard references (e.g., 17,000 vs. 14,300 K for B6 stars), as the hydrogen opacity is lower at infrared wavelengths; we observe a lower (and therefore hotter) layer in the stellar atmosphere (see Durré et al. 2017). After telluric correction and flux calibration, the data cubes from the SINFONI $H+K$ observations for separate dates were combined into single cubes. These were centered on the brightest pixel (in the image created by collapsing the cube along the wavelength axis). The whole observed field for the $H+K$ filter is 3″ × 3″, which equates to 600 × 600 pc.

Initially, the $J$ SINFONI cube showed a strong telluric absorption feature at 1268.9 nm; normally this is not an issue, but for this object, the redshift moved the [Fe ii] 1257 nm line to this wavelength and produced a pronounced “notch” in the emission-line spectrum. This was corrected by using the TRAF telluric procedure, which shifts and scales the telluric spectrum to best divide out features from data spectra by minimizing the rms error. The comparison between the telluric spectrum and a spectrum from the cube of the nuclear region showed a shift of 0.8 pixels, which, when applied to the data cube, reduced the feature considerably.

The well-known “instrumental fingerprint” in the SINFONI $J$ data cube was characterized by PCA tomography (Menezes et al. 2014, 2015); this fingerprint is the result of detector array persistence (see George et al. 2016). Over the characteristic broad horizontal stripe, the flux correction was substantial, in places up to ±15%. The correction was applied by interpolation over the fingerprint in the y-axis direction at each spectral pixel. For the final $H+K$ data cube, no fingerprint was visible in any of the tomograms, presumably because of the combination of cubes over four dates.

All the data cubes had some spikes and geometric artifacts, from the data reduction package (DRP) or other noise that is not removed (e.g., cosmic rays). These were manually cleaned by interpolation over the offending pixels, especially over the range of emission-line wavelengths.

To check on the wavelength calibration, the OH skyline wavelengths were measured from the off-target sky data cubes. These lines are assumed to be very narrow, and the wavelengths

### Table 2

| Date       | Program ID/PI     | Instrument/Filter     | Plate Scale (arcsec)$^a$ | Exp. Time$^c$/Frames | Total Exp. Time (s) | Air Mass/Seeing (arcsec)$^b$ | Standard Star | $R^g$ | $\Delta V^h$ | FOV (pc)$^d$ | Sp. Res.$^h$ (pc pixel$^{-1}$) |
|------------|-------------------|-----------------------|---------------------------|----------------------|----------------------|-----------------------------|---------------|------|-------------|-------------|-----------------------------|
| 2014 Apr 11 | 093.B-0461(A)/Mould | SINFONI $J$           | 0.25                      | 300/6                | 1800                 | 1.085/1.3                   | HIP091038     | 2400 | 11.6/53     | 1500        | 25                         |
| 2015 Feb 23 | 093.B-0597(B)/Davies | SINFONI $H+K$         | 0.1                       | 300/6                | 1800                 | 1.011/1                    | HIP073266     | 1560 | 28.3/85     | 600         | 10                          |
| 2015 Mar 5  | 093.B-057(B)/Davies | SINFONI $H+K$         | 0.1                       | 300/6                | 1800                 | 1.012/1.25                 | HIP071451     | 1560 | 25.8/85     | 600         | 10                          |
| 2015 Jun 14 | 093.B-057(B)/Davies | SINFONI $H+K$         | 0.1                       | 300/6                | 1800                 | 1.016/1.25                 | HIP078968     | 1560 | −13.9/85    | 600         | 10                          |
| 2015 Jun 25 | 093.B-057(B)/Davies | SINFONI $H+K$         | 0.1                       | 300/6                | 1800                 | 1.203/0.75                 | HIP082670     | 1560 | −21.8/85    | 600         | 10                          |
| 2016 Apr 3  | 097.B-0640(A)/Gadotti | MUSE $V$             | 0.2                       | 480/1                | 480                  | 1.048/0.66                 | ...$^i$       | 1800 | 15.5/70     | 12800       | 40                          |

$^2$ http://simbad.u-strasbg.fr/simbad/

$^3$ http://www.gemini.edu/sciops/instruments/midir-resources/imaging-calibrations/fluxmagnitude-conversion

References:

- Menezes et al. 2014
- Menezes et al. 2015
- George et al. 2016
- Wright & Eastman 2014
- Skrutskie et al. 2006
- Durré et al. 2017
are published in Rousselot et al. (2000). This showed a wavelength shift of $\sim$0.44 nm, equivalent to $\sim$62 km s$^{-1}$; this value is used in the computation of the systemic velocity of the galaxy.

### 3. Results

#### 3.1. The Nucleus of NGC 5728

The nucleus of NGC 5728 is highly complex, as revealed by multivavelength images taken at high spatial resolution, with evidence of star formation, radio and X-ray jets, and distorted kinematics. Figure 2 shows the $i$-band image from the MAST Pan-STARRS image cutout facility, overlaid with the contours of the VLA 20 cm large-scale map. It also shows the HST F160W structure map combined with the VLA 6 cm map. The VLA images (Schommer et al. 1988) were acquired from the NRAO Science Data Archive, as set out in Table 3. There are two sets of 20 cm VLA data: large scale with 5$''$ spaxels and small scale with 0$''$.3144 spaxels; the beam size given is the half-power beam width for the antenna configuration and frequency (from the NRAO resolution table). The HST structure map (Pogge & Martini 2002) produces an image defined as

$$ S = \left( \frac{I}{I \odot P} \right) \otimes P, $$

where $I$ is the original image, $P$ is the HST point-spread function (PSF) from the TinyTim software (Krist et al. 2011), $P^T$ is the transpose of the PSF, and $\otimes$ is the convolution operator.

The structure map enhances the nuclear bar and ring, with the whole central structure looking like a miniature barred spiral. The spiral aspect appears close to face-on, which is different from the rest of the galaxy. Prada & Gutiérrez (1999) found that the core is counterrotating with respect to the main galaxy and considered that it was most probably caused by orbital instabilities associated with the secondary bar; however, they could not rule out satellite or gas accretion with negative angular momentum. The filamentary dust lanes delineate the cold-phase fueling flows into the SMBH (see, e.g., Simões Lopes et al. 2007; Mezcua et al. 2015).

The 20 cm large-scale map (Figure 2) shows nuclear emission combined with two regions coincident with the star formation at the end of the galactic bar. At 6 cm, the higher spatial resolution nuclear emission shows an annulus structure, with the highest emission coincident with the structure map outer ring/arms. It also shows a jet in the NW–SE direction, aligned with the ionized gas emission.

Figure 3 displays the VLA 6 cm fluxes at three different intensity scalings, to respectively enhance the jet and star-forming (SF) ring. Masking out all pixels that have a value $\geq 300$ mJy (to remove the jet; bottom left panel), the SF ring is seen as a string of emission features, each with roughly the same luminosity ($\sim$2 mJy), which are probably individual supernova remnants (SNRs). The VLA 20 cm high-resolution map presents a very similar structure (not mapped here). Aligning the 6 and 20 cm high-resolution maps allows measurement of the spectral index; this is also plotted in Figure 3. The spectral index is computed as $\alpha = \Delta \log(S_\nu)/\Delta \log(\nu)$ and is in the range of $-1.7$ to 0.3, with a median value of $-0.8$, indicating nonthermal (i.e., synchrotron) emission.

Figure 4 shows the elliptical model fit to the Pan-STARRS image, using the IRAF stdas.analysis.isophote ellipse and bmodel tasks. The parameters for the various features are given in Table 4. The “ellipticity” is $e = 1 - b/a$, where $a$ is the major-axis size and $b$ is the minor-axis size (a smaller value means closer to circular), from which, assuming circular symmetry, the inclination $i$ of the ellipse to the LOS can be derived. This will become important in determining the inclination to the LOS of the jet.

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Table 3

| Obs. Date | Wavelength (cm) | Freq. (GHz) | Pixel Scale (arcsec) | Beam Size (arcsec) |
|-----------|-----------------|-------------|----------------------|------------------|
| 1994 Apr 18 | 20 | 1.4 | 0.3144 | 1.3 |
| 1988 Mar 23 | 20.1 | 1.49 | 5 | 14 |
| 1984 Jan 14 | 6 | 4.86 | 0.3259 | 1.0 |
Figure 5 shows the \[\text{O III}\] MUSE flux image (see below) overlaid with the \textit{Chandra} X-ray contours (acquired from the \textit{Chandra} Source Catalog, Evans et al. 2010, using the CSCView tool\(^8\)) and the VLA 6 cm contours. The X-ray and \[\text{O III}\] fluxes are cospatial. The X-ray data have been smoothed by a Gaussian with a 2 pixel FWHM, to prevent pixelation. The X-ray orientation has the highest flux in the SE direction, counter to the radio jet; this can be explained by obscuration of the NW X-ray jet, plus relativistic beaming of the NW radio jet over the SE counterjet. Rodríguez-Ardila et al. (2017), studying NGC 1368, deduce that the extended X-ray emission in that object is caused by shocks greater than 200 km s\(^{-1}\) producing free–free emission; as will be seen in Paper II, the outflow velocities of NGC 5728 certainly exceed that value.

3.2. The NIR and Optical Nuclear Spectrum

The nuclear spectrum was obtained by integrating the flux in a circular aperture of radius 0\(^{\prime}\)5 around the brightest pixel in the continuum image for the SINFONI and MUSE data cubes. Figure 6 gives the spectra for the whole NIR wavelength range, showing the good flux calibration between the data cubes, taken at different dates and instruments. For comparison, the spectrum from the 0.8–2.4 \(\mu\)m atlas of AGNs (Riffel et al. 2006) is also plotted (rescaled for clarity). Figure 7 shows the detail for the main emission lines of interest. The optical MUSE nuclear spectrum is presented in Figure 8, showing the Seyfert 2-like narrow emission lines of hydrogen, oxygen, nitrogen, and sulfur. It also shows smooth flux continuity with the NIR spectrum.

3.3. Continuum Emission

We can examine the nuclear structure, stellar populations, and obscuring dust using continuum imagery. As the J-band cube has poorer observational resolution (0\(^{\prime}\)25 with no AO), we will only use the \(H+K\) cube (0\(^{\prime}\)05 with AO). The \(H\) and \(K\) continuum magnitude images are derived from the cube by measuring the average flux over 10 nm around the 2MASS filter effective wavelengths (\(H = 1662\) nm, \(K = 2159\) nm), converting to mag arcsec\(^{-2}\) for each pixel, and deriving the color \(H−K\). Figure 9 presents the magnitude and color maps for the central 3\(^{\prime}\)8 (760 \(\times\) 760 pc).

The dust lane (starting at \(\Delta R.A. = +1\)\(^{\prime}\), \(\Delta decl. = 0\)\(^{\prime}\)) to the radio jet; this can be explained by obscuration of the NW X-ray jet, plus relativistic beaming of the NW radio jet over the SE counterjet. Rodríguez-Ardila et al. (2017), studying NGC 1368, deduce that the extended X-ray emission in that object is caused by shocks greater than 200 km s\(^{-1}\) producing free–free emission; as will be seen in Paper II, the outflow velocities of NGC 5728 certainly exceed that value.

\(^8\) http://cxc.cfa.harvard.edu/csc/, Dataset ID ADS/Sa.CXO/CSC/Reg/4077-1-P-2-0003.

Figure 3. AGN and circumnuclear SF activity from VLA 6 cm images. Top left: linear scaling (to enhance the jet). Top right: logarithmic scaling (to enhance the SF ring). Bottom left: jet masked to show point-source SNR emission. All flux values are in mJy. Bottom right: spectral index derived from 6 and 20 cm fluxes; the negative index indicates nonthermal (i.e., synchrotron) emission.
hot dust in the equatorial plane of the AGN, which also is the source of the very red colors at the nucleus; this is the equatorial toroidal obscuration component. The $H-K$ image also shows reduced obscuration in the SE and NW quadrants; the edges of these (at <0.2 mag) align with the edges of the cones (as revealed by the channel maps presented in Paper II), especially in the SE.

Figure 10 (left panel) shows the structure map for the central 16″ of the HST F814W image, clearly showing the feeding filaments in the inner spiral structure. The right panel then overlays the $K$-band magnitude contour over the central 3″8. The dark lanes are seen as the extension into the center of the feeding filaments.

### Table 4

| Feature      | Mag | SMA (pc) | PA (deg) | $\epsilon$ | $i$ (deg) |
|--------------|-----|----------|----------|------------|-----------|
| Inner bar    | 9.0 | 370      | 82       | 0.446      | 56        |
| Inner ring   | 10.5| 1045     | 20       | 0.128      | 29        |
| Main disk    | 12.5| 4800     | 27       | 0.452      | 57        |
| Outer ring   | 14.0| 13200    | 32       | 0.580      | 65        |

**Note.** Column (2): approximate limiting magnitude of the feature. The semimajor axis (SMA), position angle (PA), and ellipticity ($\epsilon$) are from the ellipse model fit. PA is N = 0°, E = 90°, $i$ = 0° is face-on to LOS; $i$ = 90° is edge-on to LOS.

Figure 5. Chandra+VLA+[O III]. [O III] flux image (logarithmic scaling) from MUSE data (flux values as per color bar), showing photoionized and shocked gas in the cones. Chandra (0.5–7 keV) smoothed flux contours (blue) have values of 0.1, 0.2, 0.5, 1, 2, and $5 \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$; this shows the reflected AGN emission plus production from shocked gas. VLA 6 cm contour (green) flux levels are at 0.2, 0.5, 1 and 2 mJy, delineating the synchrotron emission from the relativistic jet. The X-ray, radio, and emission-line gas structures are clearly aligned.

### 3.4. Gas Line Emission

Emission lines diagnose various physical parameters in the ISM, including star formation and outflow dynamics, as well as...
the physical processes of excitation. Table 5 shows the flux (with uncertainty) for the observed emission lines in the central 1″ of the nucleus, from the J, H+K, and MUSE cubes. It will be noted that the observed central wavelengths do not exactly correspond to the redshifted air wavelengths, especially in the NIR. This comes from the biased wavelengths of the multiple kinematic components, where the receding gas dominates over the approaching gas; with the ionized species lines in the cones (hydrogen recombination, [Fe II], and [Si VI]) show a recession velocity 150–250 km s⁻¹ over systemic. The H₂ lines, which are not kinematically or spatially associated with the ionization cones, have wavelengths closer to the systemic values.

We derive maps of the gas emission fluxes from the velmap (velocity map) procedure in QFitsView on the SINFONI data cubes (J and H+K). This procedure fits a Gaussian curve for every spaxel at the estimated central wavelength and FWHM. This generates maps of the best-fit continuum level (C), height (H), central wavelength (λ), and FWHM. These are readily converted to the dispersion (σ), the flux (F), and the emission equivalent width (EW). Maps were obtained for the species Paβ (1282 nm), Brγ (2166 nm), [Fe II] (1257 and 1644 nm), H₂ (2121 nm), and [Si VI] (1964 nm). We note that the Brγ and [Si VI] maps have already been presented in Shimizu et al. (2018), in the context of reevaluating the broad Hα component for Seyfert 1.9 classifications, where misclassification is caused by the presence of strong, AGN-driven outflows.

Map values are accepted or rejected based on ranges on each of the derived parameters produced by the procedure, based on visual inspection of the fluxes and kinematic structures, i.e., the derived values of continuum, line flux, LOS velocity, or dispersion have to be within certain values. Single pixels may be rejected because of large excursions from their neighbors; the source of anomalous values is usually noise spikes in the

Figure 6. Nuclear spectrum from central 1″ from SINFONI (J and H+K), plus the NIR atlas of Riffel et al. (2006). Emission lines and CO absorption band heads are marked. The NIR atlas spectrum is rescaled and offset for clarity. All spectra are reduced to rest frame.

Figure 7. Enlarged SINFONI spectra from Figure 6, showing the main lines. Spectra are reduced to rest frame.
data or low flux values, causing poor model fits. Rejected pixels are then interpolated over from neighbors or masked out, as appropriate.

The [Si VI] maps were difficult to produce owing to the close and strong H2 (1957 nm) line; since the range of velocities over the whole field is fairly large, the velmap routine was “locking on” to the wrong line in places. This was solved by creating the maps for the H2 line and then subtracting a Gaussian fit at each spaxel from the fitted parameters; this had the effect of removing the H2 line from the data cube. Additionally, the fitting procedure was done independently for the north and south halves of the data cube and then combined, as the H2 velocity field is oriented in that direction. The [Si VI] line was then fitted successfully.

We also obtained emission-line maps from the MUSE data cube in a similar manner. To increase the signal-to-noise ratio (S/N), especially in the outer regions where the gas emission is weak, we use the “Weighted Voronoi Tessellation” (WVT) method (Cappellari & Copin 2003), using the voronoi procedure in QfitsView. This aggregates spatial pixels in a region to achieve a target S/N. This needs both signal and noise maps; these are obtained at each spaxel by the data and the square root of the variance from the MUSE data cube, both averaged along the spatial axis. After some experimentation, the target S/N was set to 60. We obtained maps of the species Hα, Hβ, [O III] (500.7 nm), [S II] (671.6, 673.1 nm), [N II] (654.8 nm), and [O I] (630.0 nm). These maps were masked to a minimum flux level for each species and to remove the bright star some 19″ NE of the nucleus.
3.4.1. Emission-line Morphology

Figures 11–14 shows the flux and EW for each species. The J-band maps have a spatial extent of 7'5 square, as against the H±K band of 3' (1.5 vs. 0.6 kpc; the FOV of H±K is overplotted on the Paβ flux map). The hydrogen recombination emission, [Fe II], and coronal [Si VI] lines all show similar structure of a biconal outflow with a PA = 140°–320°; the EW maps show this clearly (the EW is invariant to obscuration), displaying a distinct “waist” at the cone intersections; this shows that there is significant stellar continuum in front of the emission and obscuration along our LOS. By contrast, the H2 is spatially distinct, presenting as a disk oriented roughly NS with “arms” trailing to the NW and SE. As we will show in Paper II, it is also kinematically distinct.

The MUSE Hα and [O III] maps show a similar picture, with a greater FOV of 30' × 30' (6 × 6 kpc; Figure 13). The ionization cones can easily be traced with the [O III] emission up to 2.5 kpc from the nucleus. The Hα emission also clearly shows the SF ring. Many H II regions are visible in a ring of approximately 7 kpc radius around the nucleus; these trace the faint spiral arms from the outer ring to where they join the nuclear structure, especially SE of the SF ring, where there is a short extension pointing SW.

3.4.2. Coronal Line Emission

Emission lines of highly ionized species (e.g., [Si VI], [Ca VIII], and [S IX]) trace the direct photoionization either from EUV and soft X-rays from the AGN accretion disk or by fast shocks. These species have IPs up to several hundred eV and are called CLs, and the emission locations are called CL regions (CLRs). This emission has the advantage of not being contaminated by photoionization from star formation, i.e., it is diagnostic of AGN activity. For coronal species with an IP of ~100–150 eV, the emission exhibits a similar morphology and kinematics to lower-ionization lines such as [O III]; however, for species with IP > 250 eV, the emission is very compact.

Mazzalay et al. (2013a) found for NGC 1068 that the morphology and kinematics were consistent with being driven by the radio jet and that shock mechanisms were favored over photoionization. A similar conclusion was deduced for NGC 1368 by Rodríguez-Ardila et al. (2017).

Apart from the [Si VI] emission, we also detect weak [S IX] and [Ca VIII] CLs. This is in contrast to Rodríguez-Ardila et al. (2011), who reported no detectable flux for those species for NGC 5728, in their CL study of 54 local AGNs. We constructed flux maps of these species by averaging the data cube along the spectral axis over the emission-line profile and then subtracting the average continuum in a neighboring featureless spectral region; the result was multiplied by the line profile width to produce the flux. The weakness of the flux precluded using the standard velmap procedure. Figure 15 plots the flux maps; the weakness of the lines will cause some uncertainties, so the flux values should not be taken as very accurate; however, the structure is clear.

The CLR, as delineated by the [Si VI] emission, extends almost to full length of the NLR, out to 300 pc in each direction from the AGN. This indicates strongly collimated hard UV–soft X-ray flux from the AGN. While the [Si VI] flux scales reasonably well with the Brγ flux, there is an impression from the morphology that the production mechanism is different between the two cones; the SE emission is in a conal form, as would be expected from direct ionization from the AGN EUV field. By contrast, the NW emission outlines, rather than in fillings, the cone; this is clearer in the EW plots than in the flux plots. This indicates that shock mechanisms predominate in the NW.

The [S IX] emission (IP = 379 eV, λ = 83.3 nm) shows a small extension along the line of the SW cone, while the [Ca VIII] (IP = 147 eV, λ = 8.4 nm) exhibits a more compact structure around the AGN location, with a possible extension along the NW cone; both of these extensions are close to the observational resolution limits. Neither of these species shows the same spatial extent as [Si VI]; in the case of [Ca VIII] (which has a similar IP to [Si VII]), the low line strength means that the flux level drops below the detectable threshold; in the case of [S IX] an additional factor could be that the ISM fully absorbs the ionizing radiation closer to the AGN. We can also posit that the higher IP species are ionized directly by the AGN, while the [Si VI] emission is also generated by shock excitation in the ionization cones, which do not have enough energy to excite the higher IP species.
### Table 5

Integrated Flux for Emission Lines for the Central 1″ (0.5″ Radius) Aperture, with Their Respective Uncertainties ($\Delta F$)

| Data Source Species | $\lambda$ (Obs) | $\lambda$ (Air) | $F$ | $\Delta F$ |
|---------------------|-----------------|-----------------|-----|----------|
| MUSE                |                 |                 |     |          |
| $H_\beta$           | 491.1           | 486.1           | 75.72 | 3.11   |
| [O III]             | 509.0           | 495.9           | 349.15 | 20.90  |
| [O III]             | 505.8           | 500.7           | 1039.59 | 53.67  |
| [N II]              | 525.0           | 519.8           | 11.99 | 1.60    |
| [Ar III]            | 615.1           | 608.9           | 12.91 | 1.27    |
| [O I]               | 636.3           | 630.0           | 41.17 | 1.40    |
| [S II]              | 642.8           | 636.0           | 13.07 | 0.94    |
| [N II]              | 661.4           | 654.8           | 129.80 | 12.0   |
| $H_\alpha$          | 662.9           | 656.3           | 357.30 | 13.31  |
| [N II]              | 664.9           | 658.3           | 462.6 | 12.3    |
| [S II]              | 678.5           | 671.6           | 103.63 | 3.23    |
| [S III]             | 679.3           | 673.1           | 101.66 | 2.97    |
| [Ar III]            | 720.8           | 713.8           | 36.57 | 1.78    |
| [O II]              | 739.3           | 732.0           | 5.81 | 0.88    |
| [Ar IV]             | 740.4           | 733.0           | 11.81 | 1.16    |
| [Si II]             | 783.0           | 775.0           | 10.49 | 0.78    |
| [S III]             | 916.1           | 906.9           | 128.00 | 6.20   |

| SINFONI J          |                  |                  |      |          |
| Pa $\gamma$        | 1105.3           | 1094.1           | 13.94 | 1.01    |
| He II              | 1197.2           | 1185.5           | 7.78 | 1.28    |
| [P II]             | 1201.3           | 1188.6           | 19.01 | 2.20    |
| C I (?)            | 1216.7           | 1204.9           | 9.77 | 0.98    |
| [Fe II]            | 1269.4           | 1256.7           | 39.47 | 2.57    |
| Pa $\delta$        | 1295.3           | 1282.2           | 40.88 | 1.64    |

| SINFONI H+K        |                  |                  |      |          |
| [Fe II]            | 1660.4           | 1643.6           | 35.88 | 3.97    |
| H$_2$ 2−1 S(5)     | 1964.2           | 1944.9           | 8.26 | 2.06    |
| H$_2$ 1−0 S(3)     | 1976.3           | 1957.6           | 48.96 | 2.18    |
| Si VI              | 1983.5           | 1964.1           | 77.10 | 2.72    |
| H$_2$ 1−0 S(2)     | 2053.2           | 2033.8           | 18.10 | 0.62    |
| He I               | 2078.8           | 2059.5           | 7.45 | 0.71    |
| H$_2$ 2−1 S(3)     | 2093.3           | 2073.5           | 3.27 | 0.60    |
| H$_2$ 1−0 S(1)     | 2142.1           | 2121.8           | 45.56 | 2.13    |
| H$_2$ 2−1 S(2)     | 2174.5           | 2154.2           | 4.37 | 1.12    |
| Br$\gamma$         | 2187.3           | 2166.1           | 17.94 | 1.09    |
| H$_2$ 3−2 S(3)     | 2221.5           | 2201.4           | 0.56 | 0.25    |
| H$_2$ 1−0 S(0)     | 2244.5           | 2223.5           | 10.58 | 0.90    |
| H$_2$ 2−1 S(1)     | 2269.1           | 2247.7           | 6.44 | 0.51    |
| H$_2$ 1−0 Q(1)     | 2429.6           | 2406.6           | 41.15 | 1.79    |
| H$_2$ 1−0 Q(2)     | 2435.6           | 2413.4           | 7.80 | 1.36    |
| H$_2$ 1−0 Q(3)     | 2446.8           | 2423.7           | 36.49 | 1.82    |

Note. Flux values are in $10^{-16}$ erg cm$^{-2}$ s$^{-1}$. Measurements are grouped by data source.

3.5. Locating the AGN

In Seyfert 2-type galaxies, the AGN is obscured by the dusty torus, so the small, unresolved BLR is not visible; this torus can extend from 0.1 to tens of parsecs (Hopkins & Hernquist 2006; Elitzur 2008; Netzer 2015), depending on AGN luminosity. The position of the AGN is usually taken as the brightest pixel in the continuum (on the assumption that there is a nuclear cluster), but in this case there is a dust lane that obscures this location, as seen on the $H-K$ color map (Paper I). This lane is in addition to the supposedly compact dusty torus, as it extends across the field for ~400 pc and connects to the spiral feeding filaments.

Presumably, the ionization cones have their origin (both positionally and kinematically) at the AGN central engine; however, there are issues that will affect the symmetry of the observed flux and velocity fields:

1. Obscuration: the dust lane is on the approaching side; this will reduce the flux (and corresponding flux-weighted velocity).
2. ISM impact: the SW velocity field shows an increase out from the AGN to a maximum of about 350 km s$^{-1}$ at 300 pc from the AGN and then a deceleration to 150 km s$^{-1}$ at 760 pc (projected distances); if the outflow encounters a denser ISM (associated with increased obscuration), this will reduce both the distance to and the velocity of the maximum.
3. Velocity bias: even without obscuration, an outflow that has a significant component of velocity along the LOS will have the approaching velocities biased toward zero, as described by Lena et al. (2015), where approaching clouds preferentially show their nonionized face to the observer; thus, their line emission is attenuated by dust embedded in the cloud, and the average velocity measured for the blueshifted clouds is skewed toward smaller values.

We deduce the position of the AGN by three different methods, each of which is plotted in Figure 16, which shows the magnified central region (1″ = 20 pixels per side). These are derived from the following:

1. The centroid/maximum of the $H_2$ flux, assuming that this is kinematically cold and settled around the center of mass of the nucleus. The [Fe II] (1644 nm), $H_\alpha$, and Br$\gamma$ flux maxima locations are also plotted for comparison.
2. The [Si VI] flux is presumably generated by direct photoionization from the AGN, and thus the peak value will be on the AGN location.
3. The $H+K$-band flux ratio of [Fe II] and Br$\gamma$ shows that the [Fe II] jackets the Br$\gamma$, thus defining the edges of the cones. The cone edges are plotted as lines; these are derived from the [Fe II] zero velocity channel map (see Paper II).
4. The continuum centroid positions are plotted for $H+K$ wavelengths at 1400 nm, then in 100 nm increments from 1600 to 2400 nm. This assumes that the flux peak moves closer to the AGN as the obscuration becomes less important at longer wavelengths.
5. The lines that join the peaks of the velocity extrema (maximum and minimum) for [Fe II] (1644 nm) and Br$\gamma$ are also plotted—there is some uncertainty in defining these lines, as the extrema locations are not well defined.

All points are assumed to have a positional error of ±1 pixel. The $H_2$ flux, the continuum centroid trajectory, and the outflow edges all seem to align to within ±2 pixels.

The final AGN location is taken to be the centroid of the locations of the $H_2$, Br$\gamma$, and [Si VI] flux maxima centroids and the [Fe II] bicone center, plus the location of the maximum of the image at 2400 nm; this is marked as the yellow star in Figure 16. We did not include the [Fe II] flux maximum, as this is only excited in low-ionization regions, i.e., away from the central AGN source. If we assume that the AGN location is the same as the Chandra compact, 2–7 keV X-ray source, this is
R.A. = 14^h 42' 23.883, decl. = -17° 15' 11.25 (Evans et al. 2010, with typical 0.6 precision).

We can match the AGN location on the $J$-band data cube by following the trajectory of the flux peak with wavelength. This is plotted at 1140 nm, then in 50 nm increments from 1200 to 1350 nm. We equate the continuum centroid at 1350 nm in $J$ with that at 1460 nm in $H+K$, displaced to follow the trend of the trajectory with wavelength. These positions are shown on previous and subsequent maps with a plus sign. Further support for the determination of the AGN location is given by the close alignment with the stellar velocity kinematics and the maximum velocity gradient of the gas kinematics.

4. Discussion

4.1. Gaseous Excitation

4.1.1. Infrared Diagnostics

Excitation mechanisms broadly fall into two categories: (1) photoionization by a central, spectrally hard radiation field (from an AGN accretion disk) or by young, hot stars (UV ionization and recombination or collisional heating), or (2) thermal heating, which can be either by shocks (from AGN outflows, SNRs, star formation, asymptotic giant branch stellar winds, or radio jet interaction) or by UV/X-ray heating of gas masses. H$_2$ is also excited by UV pumping and fluorescence (Black & van Dishoeck 1987). The emission-line spectra flux ratios enable determination of the particular or mixture of mechanisms. We derive excitation mode diagnostic diagrams from the emission-line ratios [Fe II] 1257 nm/Pa$\beta$ and H$_2$/Br$\gamma$. Nuclear activity for NIR emission line objects can be categorized by a diagnostic diagram (Larkin et al. 1998; Rodríguez-Ardila et al. 2005), where the log of the flux ratio of H$_2$/Br$\gamma$ is plotted against that of [Fe II] (1257 nm)/Pa$\beta$. This is analogous to the BPT diagrams (Baldwin et al. 1981) commonly used in the optical regime (e.g., Kewley et al. 2006). Following the updated limits from Riffel et al. (2013a), the diagram is divided into three regimes for SF, starburst (SB; dominated by H II regions), and AGN, i.e., subjected to the radiation field from the accretion disk and low-ionization nuclear emission-line region (LINER) excitations, where shocks from supernovae (SNe) and evolved stellar outflows dominate. Transition objects (TOs) have a mixture of excitations and can be subdivided by the diagnostic ratios into those where [Fe II] dominates and those where H$_2$ dominates.

As we do not have the $J$- and $K$-band data at the same spatial scale, the $J$-band diagnostic ratio ([Fe II] 1257 nm/Pa$\beta$) is recalibrated to the ratio ([Fe II] 1644 nm/Br$\gamma$) in the $H+K$ band, using the ratios ([Fe II] 1257/1644) and (Pa$\beta$/Br$\gamma$) as given in Table 6.

The diagnostic emission lines are convenient; the pairs are close together in wavelength, removing the dependency on calibration accuracy and differential extinction. The table has been supplemented with the expected ratio regimes for [Fe II] 1644 nm/Br$\gamma$ for $H$ and $K$ combined spectra, taking the ratios Pa$\beta$/Br$\gamma$ = 5.88 and [Fe II] 1257/1644 nm = 1.36. If this ratio is used, the fluxes must be corrected for extinction.
Figure 12. Same as for Figure 11, but for Br$_\gamma$, Pa$_\alpha$, H$_2$ (2121 nm), [Fe II] (1644 nm), and [Si VI]. The [Si VI] has nearly the same extent as the hydrogen recombination emission. The SF ring is outside the scale of the maps.
The $H+K$-band diagnostic ratios are shown in Figure 17 (top left and right panels). Normally, extinction correction is not required as the line pairs are close together; however, the [Fe II] 1644 nm flux values must be multiplied by 1.17 to correct for the extinction relative to Brγ in this case, taking a value of $A_V = 2.6$ from Section 4.2, below. Figure 17 also shows (bottom right) the density of all pixels that have a measurement of both ratios on the excitation diagnostic diagram; the labels correspond to the locations on the [Fe II] 1644 nm/Brγ map, i.e., the nucleus (“N”), the two cones (“1” and “2”), and an off-axis location (“3”).

Overall, the excitation mode diagram shows no “pure” photoionization/SF mode, with the vast majority of pixels in the AGN mode region, with some LINER and TO excitation. Figure 17 (bottom left) shows the predominating mode at each spatial location, as defined by the regions outlined in the bottom right panel. The colors denote the mode, as defined in the caption; the “TO” regions have been divided into that which is dominated by excess H$_2$ and that dominated by excess [Fe II] emission. The plot shows the predominance of the AGN mode, with a TO ([Fe II] excess)/LINER at the cone end caps and TO (H$_2$ excess) at the “waist.”

The correlation between the two sets of ratios on a spaxel-by-spaxel basis is weak or nonexistent ($R^2 = 0.044$), unlike that found for, e.g., IC 630 (Durré et al. 2017) and for IC 4687, but similar to NGC 7130 (Colina et al. 2015). This is due to the multicomponent nature of this object; IC 630 is an SB galaxy and IC 4687 a prototype SF luminous infrared galaxy (LIRG), whereas NGC 7130 has a mixture of SF regions and compact AGN excitation. Davies et al. (2016) have presented computations of AGN and SF mixing ratio for NGC 5728 from WiFeS optical observations on a 1″ scale (the S7 survey), where there is a clear trajectory of excitation. From our observations, this diagnostic is not possible for the nuclear region from infrared observations at high resolution because of the mixture of ionizing and thermal processes at any one LOS.
The standard division of the NIR excitation diagram into H II regions, AGNs, LINERs, and TOs is a little misleading, as what is being plotted is excitation mechanism, i.e., photo-ionization and recombination versus thermal processes (heating plus shocks). Especially in the bottom left corner of the diagram, the source can be either photoionization by young hot stars (UV) or accretion disk radiation (EUV/soft X-rays). In the [Fe II] 1644 nm/Brγ ratio plots, the cones show low ratios; however, these are not generated by hot, young stars, but by the AGN radiation field, as shown by the [Si VI] flux. [Si VI] has an IP = 167 eV (extreme UV/X-ray—7.4 nm), which fully ionizes [Fe II] to [Fe III] (which has an IP 16.2 eV); therefore, the ratio of [Fe II]/Paβ will be reduced in the ionization cones, which is exposed directly to the AGN radiation. This is also illustrated by the X-ray image (Figure 5).

We distinguish between excitation sources at a particular location by examination of the continuum and emission-line maps, as well as the diagnostic ratios. From Figure 17 (top left), for the [Fe II]/Paβ ratios, we can see that there is almost no “pure” star formation, except in the ring around the edge of the field (the 1.6 kpc ring). The ionization cones, unsurprisingly, show mainly AGN excitation, with a mixture of AGN and LINER excitation surrounding it. The actual mode in the periphery will be somewhat uncertain, as the flux values are low, with correspondingly larger uncertainties. By contrast, the H2/Brγ ratios have a different structure; this is due to the molecular hydrogen being decoupled both spatially and kinematically from the cones. This is also shown by the velocity and dispersion histograms; the [Fe II] and hydrogen recombination absolute velocity and dispersion peaks are higher than H2 (these results will be presented in Paper II).

We can use the forbidden lines [Fe II] and [Si VI] as diagnostics for density, as above a critical density \(n_{cr}\) for each species the emission is suppressed because of rapid collisional de-excitation (Rodríguez-Ardila et al. 2011). For [Fe II], this is of the order \(n_{cr} = 10^5\) cm\(^{-3}\); for [Si VI] this is \(n_{cr} = 6.3 \times 10^8\) cm\(^{-3}\). This indicates that the densities inside and outside the cones could be different by several orders of magnitude.
4.1.2. Optical Diagnostics

We also constructed BPT diagrams from the MUSE data cube optical emission line maps (see Section 3.4.1). The pixel excitation density maps for [N II]/Hα, [S II]/Hα, and [O I]/Hα versus [O III]/Hβ are shown in Figure 18 (top row). We use the classification lines from Kewley et al. (2006), dividing up the diagrams into H II-region-like, Seyferts, LINERs, and composite H II AGN types. The tight distribution of the points shows a smooth transition of star formation to AGN excitation. Following Davies et al. (2014a, 2014b), this is parameterized on each diagram using a star formation/AGN mixing ratio measure, where the 0% and 100% AGN fraction is assigned to the extrema of the measured mixing sequence. The 0% mixing ratio point is shown on each plot as a green symbol, with the green dotted contour lines delineating the mixing percentage along the sequence. The 0% and 100% basis locations for the SF/AGN mixing ratios are given in Table 7.

The bottom row of Figure 18 shows the excitation mode maps for each diagnostic set, color-coded by the mixing ratio of each spaxel; there is complete consistency between the plots. Star formation/composite excitation is coded as blue, cyan, and green (with the mixing ratio $\lesssim 50\%$), with Seyfert/AGN excitation coded yellow and red (with the mixing ratio $\gtrsim 50\%$). The excitation values for several representative locations were computed for a 1″ diameter aperture; the flux values (with errors) were measured by Gaussian fits to the emission line. These locations are at the nucleus, two in the SE and three in the NW ionization cones, three on the SF ring, and two in the

### Table 6

| Excitation Mode | [H$_2$/Br$_\gamma$] | [Fe II]/Pa$^3_{\lambda 15}$ (1257 nm) | [Fe II]/Br$_\gamma$ (1644 nm) |
|-----------------|---------------------|--------------------------------------|-----------------------------|
| SF/SB           | $<0.4$              | $<0.6$                               | $<2.6$                      |
| AGN             | 0.4–6               | 0.6–2                                | 2.6–8.6                     |
| LINER           | $>2$                | $>2$                                 | $>8.6$                      |

### Table 7

| Basis Locations for SF/AGN Mixing Ratios |
|------------------------------------------|
| log([N II]/Hα) | log(S II)/Hα | log([O I]/Hα) |
|----------------|--------------|---------------|
| Basis point SF | ($-0.5,-0.8$) | ($-0.7,-0.7$) | ($-2.0,-0.75$) |
| Basis point AGN  | (0.2,1.45)  | (0.05,1.45)  | (0.7,1.45)  |
spiral arm that intersects the SF ring from the south (one near the intersection point and one at an SF site ∼26″ SW of the nucleus). The values are given in Table 8. For the nucleus, where the LOS intersects both approaching and receding gas, a multicomponent Gauss fit was required to deblend the six overlapping components (two each for Hα and [N II] 654.9, 658.3 nm). These locations are shown as numbers on the [N II]/Hα mixing ratio map; each location is plotted on the respective excitation density map (red numbers).

The electron density \(N_e\) (Acker & Jaschek 1986) and temperature \(T_e\) (Osterbrock & Ferland 2006) can also be estimated from optical diagnostics, using the [N II] and [S II] emission lines for the MUSE spectrum. The relationships are

\[ R_N = I(\lambda 654.8 + \lambda 658.4)/I(\lambda 575.4) \]  
\[ R_S = I(\lambda 671.7)/I(\lambda 673.1) \]  
\[ T_e = \frac{25000}{\ln(R_N/8.3)} \]  
\[ N_e = 10^2 T_e \left(\frac{R_S - 1.49}{5.62 - 12.8 R_S}\right). \]

where \(R_N\) is the ratio for the [N II] lines and \(R_S\) is the ratio for the [S II] lines. The alternate diagnostic for \(T_e\) using the [O III] lines (Kwok 2007) is not available in the MUSE spectral range. For the SF-dominated regions (locations “7” to “11”), the [N II] 575.4 nm was not measurable; we used an estimated temperature of \(T_e = 8000\) K, somewhat lower than the AGN-dominated locations. The calculated values are given in Table 8; while the electron temperatures are reasonably consistent (with error bars of the order of 5%–10%) in the AGN-dominated regions, the electron density has larger errors (from 25% to 70%, mainly due to the uncertainties in the flux of the weak [N II] 575.4 nm line), but there is a clear trend with lower density being at a greater distance from the AGN. \(N_e\) linearly scales with a lower assumed \(T_e\).

4.1.3. \(H_2\) Excitation

Molecular hydrogen (\(H_2\)) is very important in the star formation context of AGN activity, since it is the basic building block for stars. In the K band, there are a whole series of rotational-vibrational emission lines, which can be used to examine the excitation mechanism for \(H_2\), which can be either

1. UV photons (fluorescence) from star formation and/or AGN continuum emission (Black & van Dishoeck 1987);
2. shocks from SNe, AGN outflows, or star formation winds (Hollenbach & McKee 1989); or
3. X-rays from the AGN irradiating and heating dense gas (Maloney et al. 1996).

In reality, all these different mechanisms occur together; however, the dominating mechanism can be estimated and the contributing fractions of different mechanisms can be constrained (Busch et al. 2017).

Following the method outlined in Wilman et al. (2005), for gas with density $n_T > 10^5$ cm$^{-3}$, the thermal (collisional) temperatures can be estimated. The occupation numbers of the excited rovibrational levels of the H$_2$ molecule will be in thermal equilibrium at a temperature $T_{\text{exc}}$ equal to the kinetic temperature of the gas. This leads to the relationship

$$\ln \left( \frac{F_i \lambda_i}{A_i g_i} \right) = \text{constant} - \frac{T_i}{T_{\text{exc}}},$$

where $F_i$ is the flux of the $i$th H$_2$ line, $\lambda_i$ is its wavelength, $A_i$ is the spontaneous emission coefficient, $g_i$ is the statistical weight of the upper level of the transition, and $T_i$ is the energy of the level expressed as a temperature. The left-hand side of this equation is equivalent to $\ln(N_{\text{upper}})$, the occupation number of the upper level of the H$_2$ transition. This relation is valid for thermal excitation, under the assumption of an ortho:para abundance ratio of 3:1. The $A_i$, $g_i$, and $T_i$ for each line were obtained from online data entitled “Molecular Hydrogen Transition Data.”

At a particular location, plotting $\ln(N_{\text{upper}})$ versus $T_i$ gives a linear relationship, where the negative inverse slope is the excitation temperature $T_{\text{exc}}$.

The H$_2$ 2–1 S(3) (2073.5 nm) is diagnostic for X-ray excitation, which is expected to suppress the line, as the upper level of this transition is depopulated by a resonance with photons around the wavelength of Ly$\alpha$ at 1216 Å, which are readily generated by X-ray heating (Black & van Dishoeck 1987; Krabbe et al. 2000; Davies et al. 2005).

The flux for the H$_2$ K-band lines was measured at several locations, P1–P6, as shown in Figure 19 (top left panel). The spectrum at each location was taken from a circular region 4 pixels wide and the flux measured from a Gaussian fit to the

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Figure 18. Optical excitation (BPT) diagnostic diagrams from MUSE data. Top row: excitation pixel density map for log([N II]/H$\alpha$), log([S II]/H$\alpha$), and log([O I]/H$\alpha$) vs. log([O III]/H$\beta$). Contour levels are at 1%, 5%, 10%, and 50% of maximum density. The labels (“1”...“11”) correspond to the representative locations, as described in the text. The basis point for the star formation/AGN mixing ratio is plotted as a green symbol, with the ratio shown by green dotted contours. Bottom row: spatial excitation mode for each set of diagnostics, color-coded by star formation/AGN mixing distance.
Wilman et al. (2005), and Figure 19 (bottom panel) shows the rotation and vibrational temperatures plotted on the Mouri (1994) excitation mechanism diagram. These results show that the gas is close to the local thermodynamic equilibrium (LTE) line, indicating predominantly thermal processes. The 2–1 S(3) line is present at all locations, however, in most locations (P1, P2, P3, and P6) it is below the fitted line, indicating that X-rays make up a minor component of the excitation (e.g., Krabbe et al. 2000, for NGC 1275), with shocks probably the main contributor to the excitation.

We calculate the excitation temperatures from the inverse slope of the low-excitation ($\nu = 1 - 0$), high-excitation ($\nu = 2 - 1/3 - 2$), and all lines, respectively. These are given in Table 9. The low-excitation temperatures are very similar (1740 ± 50 K), except for the nucleus and location P6. It can be hypothesized that the H$_2$ in the LOS of the nucleus is shielded from some of the heating effect of the AGN by the circumnuclear torus or dusty bar that is visible in the $H-K$ magnitude maps (Figure 9). The radio jet impact on the ISM at location P6 could increase the excitation in that region.

If we include all the lines, the derived temperatures increase somewhat; however, the high-excitation flux values are more uncertain. These temperatures are now compatible with results for other Seyfert galaxies in the literature, in the range of 2100–2700 K (e.g., Storchi-Bergmann et al. 2009; Riffel et al. 2010, 2014, 2015; Riffel & Storchi-Bergmann 2011). The temperature derived for P5 for all lines would seem to be unphysical, being above the dissociation temperature for H$_2$. However, Davies et al. (2003, 2005) show that the lower $\nu = 1 - 0$ levels may be thermalized, but the $\nu = 2 - 1$ and $\nu = 3 - 2$ levels can be overpopulated owing to fluorescent excitation by far-ultraviolet photons. If we fit just the $\nu = 2 - 1$ and $\nu = 3 - 2$ levels, we can see that the P5 location has a very high temperature ($\sim$7000 K); this is in the NW ionization cone at the hypothesized point of impact of the radio jet with the ISM and is also presumably illuminated by the accretion disk radiation field where the fluorescent excitation is highest. Alternately, there may be a component of much hotter gas close to the H$_2$ dissociation temperature of $\sim$4000 K, or there is nonthermal emission due to excitation of the molecule by secondary electrons deep in the cloud.

The flux ratio for the 2–1 S(1) (2247.7 nm) and 1–0 S(1) (2121.8 nm) lines is diagnostic for excitation by soft-UV photons (from star formation) versus thermal processes (from shocks or X-ray heating), with a value of $\sim$0.1–0.2 for thermal and $\sim$0.55 for fluorescent processes (following Riffel et al. 2014, in their excitation study of NGC 1068). Figure 19 (top right panel) shows this plot; where there is strong H$_2$ flux, the ratios indicate purely thermal processes. Higher values at the periphery reflect an increasing contribution of excitation by hot stars away from the X-ray heating and shocks in the nuclear region, plus uncertainties in the flux measurements.

It is noted that there is a difference between the optical and IR excitation diagnostic diagrams, with the optical diagram showing a tight relationship along the mixing sequence, but the IR diagram shows a broad spread. This difference can be ascribed to the use of H$_2$ in the IR diagnostic, which incorporates different excitation mechanisms (X-ray heating and UV fluorescence) from that of the metal ions (AGN power-law radiation field).

![Figure 19](image.jpg)

Figure 19. Left panel: H$_2$ measurement locations on flux map. Contours are at 5%, 10%, 30%, and 50% of maximum flux. Right panel: H$_2$ 2248/2121 nm flux ratio. Overplotted contours are at 5%, 10%, 20%, and 50% of maximum. Thermal processes dominate at high H$_2$ flux, with an increasing contribution from UV fluorescence at lower fluxes. Bottom panel: diagnostic diagram (Mouri 1994) for H$_2$ locations. The green trajectory is for gas at LTE with the temperature indicated. The values for points P1–P6 are plotted. Thermal processes (X-ray heating and shocks) predominate.

line, using QFitsView fitting facility. The locations were chosen to be the nucleus and 0.5 N and S, in line with the rotation, plus other features visible in the flux map.

We could measure all of the low-excitation lines ($\nu = 1 - 0$); however, the high-excitation line fluxes ($\nu = 2 - 1$ and $\nu = 3 - 2$) were more uncertain. At location P4, only the 2–1 S(3) line could be measured (see Figure 20). The results for the derived parameters are given in Table 9 for the excitation temperatures.

Independently, the rotational and vibrational temperatures can be determined from two ortho/para lines that belong to the same vibrational level, e.g., 1–0 S(0) (2223.5 nm) and 1–0 S(2) (2033.8 nm), whereas the vibrational excitation temperature can be determined by connecting two transitions with the same J but from consecutive $\nu$ levels, e.g., 2–1 S(1) (2247.7 nm) and 1–0 S(1) (2121.8 nm) (Riffel et al. 2014; Busch et al. 2017). The formulae are

$$T_{\text{rot}(\nu=1)} = \frac{1113}{1.130 + \ln \left( \frac{F_{1-0(0)}}{F_{1-0(2)}} \right)} \quad (7)$$

$$T_{\text{vib}} = \frac{5594}{0.304 + \ln \left( \frac{F_{1-0(1)}}{F_{1-0(2)}} \right)} \quad (8)$$

The computed values are given in Table 10. Figure 20 shows the excitation temperature plot derived from the method of
Excitation Diagnostic Values and Estimated Electron Temperature and Density at Locations Plotted in Figure 18

| Location | $\log([\text{O III}]/H\beta)$ | $\log([\text{N II}]/H\alpha)$ | $\log([\text{S II}]/H\alpha)$ | $\log([\text{O I}]/H\alpha)$ | $T_e$ | $N_e$ |
|----------|-----------------|-----------------|-----------------|-----------------|------|------|
| 1—Nucleus | 1.13 ± 0.04     | 0.13 ± 0.02     | −0.22 ± 0.03    | −0.90 ± 0.03    | 8045 ± 361 | 50,450 ± 12,958 |
| 2—IC SE 1 | 0.89 ± 0.02     | −0.02 ± 0.02    | −0.35 ± 0.02    | −1.13 ± 0.02    | 9080 ± 802 | 21,590 ± 10,430 |
| 3—IC SE 2 | 1.04 ± 0.01     | −0.12 ± 0.02    | −0.42 ± 0.02    | −1.04 ± 0.02    | 9559 ± 659 | 15,280 ± 7516 |
| 4—IC SW 1 | 1.10 ± 0.03     | 0.14 ± 0.03     | −0.16 ± 0.04    | −0.88 ± 0.04    | 8059 ± 307 | 37,473 ± 14,909 |
| 5—IC NW 2 | 0.61 ± 0.02     | −0.17 ± 0.01    | −0.41 ± 0.01    | −1.37 ± 0.02    | 8042 ± 853 | 15,422 ± 5327 |
| 6—IC NW 3 | 1.05 ± 0.01     | 0.02 ± 0.02     | −0.20 ± 0.02    | −1.05 ± 0.04    | 8311 ± 790 | 9262 ± 6604 |
| 7—SFR 1   | −0.18 ± 0.04    | −0.29 ± 0.01    | −0.48 ± 0.01    | −1.70 ± 0.05    | 8000 9 | 11,605 ± 3374 |
| 8—SFR 2   | −0.38 ± 0.04    | −0.30 ± 0.01    | −0.47 ± 0.01    | −1.57 ± 0.04    | 8000 9 | 10,562 ± 3670 |
| 9—SFR 3   | −0.23 ± 0.03    | −0.29 ± 0.01    | −0.57 ± 0.01    | −1.73 ± 0.03    | 8000 9 | 19,503 ± 3589 |
| 10—S Arm 1| −0.15 ± 0.02    | −0.30 ± 0.01    | −0.50 ± 0.01    | −1.77 ± 0.07    | 8000 9 | 8874 ± 3931 |
| 11—S Arm 2| −0.51 ± 0.02    | −0.38 ± 0.01    | −0.70 ± 0.01    | −2.17 ± 0.08    | 8000 9 | 6963 ± 2788 |

Note. Locations are labeled as follows: "IC"—ionization cone; "SFR"—star-forming ring; "S Arm"—southern spiral arm.

* Estimated temperature.

Figure 20. H$_2$ temperature plots. The value of the inverse slope of the relationship between $\ln(N_{\text{upper}})$ and $E_{\text{upper}}$ is the excitation temperature of H$_2$ for LTE. The values are plotted for each location, each with an offset for clarity. The transitions are labeled below the plot. The $\nu = 1 - 0$ transition fits are plotted with solid lines, the $\nu = 2 - 1$ and $\nu = 3 - 2$ fits are plotted with dotted lines, and those for all transitions are plotted with dashed lines. Including the higher-excitation increases the derived temperatures, but these may not be in LTE.

4.1.4. Other Diagnostics

The [Fe II] and [Pa II] 1188.6 nm emission lines can be used to diagnose the relative contribution of photoionization and shocks (Oliva et al. 2001; Storchi-Bergmann et al. 2009), where ratios $\sim$2 indicate photoionization (as the [Fe II] is locked into dust grains), with higher values indicating shocked release of the [Fe II] from the grains (up to 20 for SNRs). This ratio was determined at three locations with a 1″ aperture: the AGN (5.9 ± 1.2), the SE cone maximum flux (5.8 ± 1.6), and the NW cone maximum flux (3.9 ± 0.7). This shows that the excitation is a mixture of shock and photoionization, with the latter predominating.

This result is confirmed by the diagnostics from Mouri et al. (2000), who calculated photoionization and shock heating models and generated diagnostic diagrams for the ratios of [Fe II] 1257 nm/Pa$\beta$ versus [O I]/H$\alpha$ for both power-law and blackbody photoionization, as well as shock heating models. From Table 5 values, the ratios within the inner 1″ are [Fe II] 1644 nm/Br$\gamma$ = 2.0 (which translates to [Fe II] 1257 nm/ Pa$\beta$ = 0.46) and [O I]/H$\alpha$ = 0.115 (from the MUSE data). These values are compatible with both power-law photoionization and shock models (favoring photoionization), where the metal abundances are subsolar and the ionization parameter is high, $U \gg 10^{-1.5}$ (see Figure 3 of Mouri et al. 2000).

We attempted to measure the electron density from the [Fe II] line ratio, from the methods described in Storchi-Bergmann et al. (2009), and from the ratios of H-band emission lines for [Fe II] 1533/1644, 1600/1644, 1664/1644, and/or 1677/1644 nm. However, all fluxes, other than the 1644 nm line, were all very weak even at the location of the peak [Fe II] 1644 nm flux. The only one that could be measured with reasonable certainty (the 1533 nm line) gave a low flux ratio (0.062 ± 0.01), which indicated a low electron density (<1000 cm$^{-3}$). This is a firm upper limit, as the 1644 nm flux is strong. This low density is
measured in the partially ionized [Fe II] line emitting region, and not close to the central engine, where it would be much higher.

4.2. Extinction

We can derive the extinction by dust from emission-line flux ratios, where the known ratio of a pair of emission lines is compared against observations and extrapolated to the $B - V$ extinction and $A_V$ (the absolute extinction in the $V$ band). In general, the formulae are as follows:

$$E(B - V) = \alpha_{\lambda_1, \lambda_2} \log \left( \frac{R_{\lambda_1, \lambda_2}}{F_{\lambda_1}/F_{\lambda_2}} \right)$$  \hspace{1cm} (9)

$$A_V = E(B - V) \times R_V,$$  \hspace{1cm} (10)

where $R_{\lambda_1, \lambda_2}$ is the intrinsic emissivity ratio of the two lines and $\alpha_{\lambda_1, \lambda_2}$ are line ratios from the emission-line wavelengths to $B - V$. $R_V$ is the total-to-selective extinction ratio; we use the fiducial value of 3.1. We use the Cardelli et al. (1989) empirical relationships to derive the $\alpha_{\lambda_1, \lambda_2}$ values. The hydrogen line ratios are from Hummer & Storey (1987), assuming Case B recombination, an electron temperature $T_e = 10^4$ K, and a density $n_e = 10^3$ cm$^{-3}$. The [Fe II] ratios in the literature are discrepant; we will use the commonly accepted value of 1.36 (see the discussion in Durré et al. 2017).

For this object, the [Fe II] 1257/1644 nm ratio will be somewhat uncertain, even with the corrected telluric feature in the 1257 nm emission line. The Pa$\gamma$/Pa$\beta$ ratio has the advantage that it is measured in the same band, but the Pa$\gamma$ gas kinematics are of poor quality owing to the line being near the short end of the spectrum and close to the edge of the atmospheric window. An attempt at calculating the extinction using this ratio produced unphysical values over the whole field. We also suspect that there is some telluric contamination, as the line width is broader than Pa$\beta$. The Pa$\beta$/Br$\gamma$ ratio can only be mapped over part of the whole central ring feature, as the $H + K$-band observations are at a smaller scale than the $J$-band ones; uncertainties are also introduced by the rescaling and any flux calibration uncertainties. The Pa$\alpha$/Br$\gamma$ ratio has the advantage that it is in the one data cube; however, the Pa$\alpha$ line is in the atmospheric absorption region between the $H$ and $K$ bands. On examination of the cube, it was seen that the Pa$\alpha$ line is very strong, and the continuum is piecewise smooth between the bands, so a definitive measurement can be made.

We derived the extinction value $A_V$ from the flux maps of Pa$\alpha$ and Br$\gamma$, with the constants as given in Table 11; unphysical values are masked out. This is shown in Figure 21, where the left panel shows the color map of the Br$\gamma$ and the contour giving the Pa$\alpha$ flux; the extinction map is plotted in the right panel. The $A_V$ values range up to 19 mag, and the extinction is strongly concentrated around the AGN, presenting as a roughly elliptical region or bar of size 64 x 28 pc (where the extinction is >16 mag), aligned at right angles to the ionization cones. This is comparable in size to the obscuring dust bar found for NGC 2110 at 55 x 27 pc (Durré & Mould 2014). The average extinction over all valid pixels is 3.7 mag.

Determining the extinction from the [Fe II] line ratio was more difficult, given the uncertainties mentioned above. The J flux map was subsampled to the same scale and aligned to the $H + K$ map by matching the flux maxima; the fluxes of the lines are shown in Figure 22 (left panel—color map is [Fe II] 1257 nm flux, contours 1644 nm flux). The values range up to 15 mag of extinction, and the morphology is comparable with the Pa$\alpha$/Br$\gamma$ maps, with some differences (Figure 23, right panel). The peak location for [Fe II] extinction is not on located on the AGN, but somewhat to the SE (∼30 pc). The morphology is also more even, with the interiors of the ionization cones having greater extinction than the Pa$\alpha$/Br$\gamma$ extinction. These values and conclusions should be treated with some caution, as it depends on the exact alignment of the two [Fe II] flux maps (e.g., a 2 pixel shift in the R.A. coordinate places the peak extinctions at the same location).

The extinction was also measured by taking a spectrum from the data cubes in an aperture of 1º diameter around the AGN location, showing $A_V = 14.9$ mag for Pa$\alpha$/Br$\gamma$ and 6.45 mag for [Fe II]. The lower values, in general, support the conclusion that the [Fe II] flux originates from a skin around the ionization cones, and thus the extinction does not probe the full depth of the cones.

Apart from the high extinction around the AGN, there is an indication that the hydrogen recombination extinction also traces the boundaries of the ionization cones; one can hypothesize that the dust (which causes the extinction) is sublimated in the AGN radiation field. To check this, the [Si VI] flux (which traces the high-ionization region and outflow shock boundaries) is plotted with the extinction from hydrogen recombination (Figure 23, left panel); the extinction traces the boundaries of the [Si VI], providing support for the hypothesis. Around the AGN, the obscuring dusty toroidal structure overlays the [Si VI] emission along our LOS.

The extinction can also be calculated at a broader scale from the H$\alpha$/H$\beta$ ratio, using the MUSE data. The intrinsic ratio for AGN NLRs is quoted as 3.1 (Davies et al. 2017, following) instead of the fiducial value of 2.86. The extinction map (Figure 24) uses this value where the AGN mixing ratio is
The obscuration caused by the dust lane is seen in Figure 9 in the \( H-K \) map and Figure 11 in the EW maps. Since the EW measure is supposedly independent of obscuration, we posit that there is significant stellar continuum in front of the gas emission and obscuration along our LOS. In the same manner, the \( \text{H}_2 \) emission is also in front of this obscuration.

### 4.3. Gas Masses

The cold gas column density can be derived from the visual extinction value. The gas-to-extinction ratio, \( N_{\text{HI}}/A_V \), varies from 1.8 (Predehl & Schmitt 1995) to 2.2 \( \times 10^{21} \) cm\(^{-2} \) (Ryter 1996). Zhu et al. (2017) find the Milky Way ratio for solar abundances to be \( \sim 2.1 \times 10^{21} \) cm\(^{-2} \); this increases to \( \sim 2.5 \times 10^{21} \) cm\(^{-2} \) for subsolar abundances. We will use a value of \( 2.0 \times 10^{21} \) cm\(^{-2} \). Using an average atomic/molecular weight of 1.4, we thus derive the relationship

\[
\sigma_{\text{Gas}} = 22.1 A_V M_\odot \text{ pc}^{-2} \tag{11}
\]

The extinction value toward the AGN implies a cold gas column density of 420 \( M_\odot \) pc\(^{-2} \), equivalent to \( N_{\text{HI}} = 4 \times 10^{22} \) cm\(^{-2} \). Davies et al. (2015) give the column density based on X-ray modeling as \( N_{\text{HI}} = 1.6 \times 10^{24} \) cm\(^{-2} \), a factor of 40 times higher. This absorption is likely to be at the parsec scale in the broad-line region (BLR; Burtscher et al. 2016), i.e., it is probing a very narrow LOS, while the recombination lines are measured over a much more extended area; also, these lines will not penetrate very deep into the obscuration, as the high extinction will attenuate the emission lines so much that they will not contribute to the measured total.

We also derive the ionized hydrogen plus warm/hot and cold \( \text{H}_2 \) gas masses, using the formulae from Riffel et al. (2013b, 2015):

\[
M_{\text{HI}} \approx 3 \times 10^{17} F_{\text{Br}} D^2 M_\odot \tag{12}
\]

\[
M_{\text{HI}} \text{(Warm)} \approx 5.0776 \times 10^{13} F_{\text{H}_\alpha} D^2 M_\odot \tag{13}
\]

\[
M_{\text{HI}} \text{(Cold)} \approx R \frac{L_{\text{HI}} M_\odot}{L_\odot}
\approx 3.12 \times 10^{16} R F_{\text{H}_\alpha} D^2 M_\odot, \tag{14}
\]

where \( D \) is the distance in Mpc and \( F \) is measured in erg cm\(^{-2} \) s\(^{-1} \), which gives \( M_{\text{Cold}}/M_{\text{Warm}} \) as \( 7.2 \times 10^5 \) and \( 2.7 \times 10^6 \).
respectively. For the Brγ emission, a standard electron temperature $T = 10^4$ K and density $n_e = 100$ cm$^{-3}$ are assumed. The $H_2$ flux is that of the 2121 nm line.

The constant $R$ is given variously as 1174 (Mazzalay et al. 2013b) for six local galaxies, or 4000 (Müller Sánchez et al. 2006) from 17 LIRG/ULIRG galaxies; these give $M_{\text{Cold}}/M_{\text{Warm}}$ as $7.2 \times 10^5$ and $2.7 \times 10^6$, respectively. The Mazzalay et al. (2013b) value is originally derived from the observed CO radio emission with estimates of CO/$H_2$ ratios (which can vary over a range of $10^{-5}$–$10^{-3}$). At the centers of galaxies hosting AGNs, this ratio could be substantially overestimated, as a greater proportion of the gas will be excited. Given this uncertainty, we will use the Mazzalay et al. (2013b) value of $R = 1174$.

Table 12 presents the results. The surface density values for the inner 100 pc radius are within the ranges of the results from Schönell et al. (2017), who summarize results for one LINER, five Seyfert 1, and four Seyfert 2 galaxies observed by the AGNIFS group; the range of HII surface densities is $1.5$–$125 M_\odot$/pc$^2$, and the range of $H_2$ (cold+warm) surface densities is $526$–$9600 M_\odot$/pc$^2$. Star formation rates and SN rates have not been calculated, as it is clear that both the hydrogen and [Fe II] excitation is caused by the AGN photoionizing source plus associated outflow shocks, rather than star formation.

The mass of warm $H_2$ over the whole observed field ($\sim 960 M_\odot$) compares well with that found derived by Rodríguez-Ardila et al. 2005 (900 $M_\odot$); the estimated total (cold) $H_2$ mass is $7 \times 10^5$–$2.6 \times 10^6 M_\odot$. Combes & Leon (2002), from radio observations of CO(1–0), deduced a total $H_2$ mass of $3.1 \times 10^9 M_\odot$, which covers the whole galactic disk, including the extended nuclear region and the SF loci at the tips of the main bar.

### 4.4. AGN Torus Properties

AGN tori typically have hot ($\sim 600$–$1000$ K) dust emission; this can be seen as an increase in the continuum slope toward the end of the K band. Figure 25 shows the ratio of the spectrum in annuli around the AGN location to that of a reference spectrum located 1″3 NW of the nucleus, which is presumably representative of the underlying stellar population. This ratio is normalized at the shortest wavelength in the spectrum (1453 nm). The changing continuum slope is indicative of an increasing hot dust contribution at smaller radii. It should be emphasized that the actual continuum slopes are always negative; the inner slopes are relatively less negative.

The inner torus directly around the AGN is encompassed within the central pixel; we can find the temperature by fitting the $K$-band spectrum for this pixel with a linear combination of the reference spectrum described above and a blackbody spectrum:

$$S_C = \alpha S_R + \beta S_{BB}(T) + \gamma,$$

where $S_C$ is the central pixel spectrum, $S_R$ is the reference spectrum, and $S_{BB}(T)$ is a blackbody spectrum at temperature $T$;

### Table 12

| Max Pixel $(M_\odot$ pc$^{-2}$) | $M_1$ 100 pc | $M_1$ 200 pc | $M_1$ Total | $M_1$ pc$^{-2}$ 100 pc | $M_1$ pc$^{-2}$ 200 pc |
|---------------------------------|--------------|--------------|-------------|-----------------------|-----------------------|
| ISM ($\sigma_{\text{Gas}}$)    | 420          | $4.9 \times 10^6$ | ...       | ...                  | 155                   |
| H II                           | 110.0        | $7.93 \times 10^5$ | $1.31 \times 10^6$ | $1.92 \times 10^6$ | 25.2                 |
| $H_2$ (warm)                   | $3.83 \times 10^{-2}$ | $388.5$ | $695.6$ | 957.2 | 1.24 $\times 10^{-2}$ | 5.54 $\times 10^{-3}$ |

Note. The extinction/ISM is not measured outside the 100 pc radius.

Figure 25. Hot dust contribution to the nuclear spectrum. Top panel: ratio of continuum in annuli around the nucleus to a nonnuclear reference spectrum, showing the long-wavelength rise indicative of hot nuclear dust. The first and second plots are apertures of radius 0″1 and 0″25, then in annuli of 0″25 up to 1″, around the nucleus. The reference spectrum is also plotted for comparison. The ratios have been offset for clarity. Bottom panel: fit to nuclear flux from reference spectrum and blackbody spectrum at 870 K. See the text for an explanation of the fitting process. The vertical axis is in arbitrary flux units. The emission lines in the nuclear spectrum have been masked out. The residual flux is also plotted at the same scale.
α, β, and γ are fitting constants. The equation was solved for T using the generalized reduced gradient algorithm (“GRG Nonlinear”) implemented in the MS-Excel add-on Solver. The emission lines have been masked out from the central pixel spectrum. The best-fit blackbody spectrum is at a temperature of 870 K; this is shown in the bottom panel of Figure 25. Burtscher et al. (2015) report median hot dust temperatures of 1292 K for Seyfert 1 and 887 K for Seyfert 2 types for 51 local AGNs; the value for NGC 5728 is in good agreement with this range.

4.5. High-ionization Emission

Murayama & Taniguchi (1998) proposed a model of a clumpy CLR associated with the NLR, where the individual clumps are “matter-bounded,” i.e., the whole cloud is ionized and its extent is simply that of the gas cloud itself. Since, under this model, receding outflows (presumably the far side of the AGN) would preferentially show the highly ionized face toward the observer, the emission should be more prominent on that side. However, our observations of the flux ratio [Si VI]/Brγ, as displayed in Figure 26, do not show significant difference between the two ionization cones.

Rodríguez-Ardila et al. (2004b) deduced that photoionization alone is not enough to generate CLs at the distances and velocities from the source that our observations show. In five of the six objects studied, the CL emission was significantly broader and asymmetric toward the blue than low-ionization lines. In contrast to their findings, the [Si VI] FWHM for our observations is virtually identical to that of Brγ, both over the whole field and specifically along the outflow axis.

The X-ray jet observed by Chandra (especially in the soft X-rays) can contribute to the photoionization of CL species. The X-rays can be generated by several mechanisms: direct photoionization from the AGN, shocks with velocities \( \geq 200 \text{ km s}^{-1} \) (Rodríguez-Ardila et al. 2017), and inverse Compton scattering of relativistic electrons associated with the radio jet. From the gas kinematics, velocities of the required magnitude are certainly present and are aligned with the [Si VI] emission generated by shocks. Figure 27 shows this alignment, where the color map shows the [Si VI] flux and the overlaid contours show the X-ray emission. The plots were aligned by equating the derived AGN location on the [Si VI] flux map with a Gaussian fit to the location of the central peak of the smoothed X-ray flux map. The absence of an X-ray jet in the NW portion of the map is most probably caused by higher gas column densities; this is certainly the region of the dust lane.

Rodríguez-Ardila et al. (2017) examined the powerful outflows in NGC 1386 and found that the [Si VI] and [Ca VIII] emission extended \( \sim 150 \) pc in one direction from the nucleus. A similar result was found by Müller-Sánchez et al. (2011) for seven Seyfert 1.5–2 galaxies; the [Si VI] emission had radial extents from the nucleus ranging from 80 to 150 pc. The largest CL so far is that of NGC 5135 (Bedregal et al. 2009), of \( \sim 600 \) pc. The CLR of NGC 5728 certainly approaches that size.
Figure 28. SF ring Hα flux for the central 10″ (note the scale in left panel). Left panel: observed flux. Middle panel: A(Hα) extinction (magnitudes). Right panel: corrected flux; the blue dashed circles show the annulus used to estimate the total SF rate. Flux values are in units of 10^{-16} erg cm^{-2} s^{-1}.

Overall, the CLR is generated by a complex mixture of photoionization (both directly from the AGN and from shock-generated X-rays further along the outflow cone) and shocks. The morphology and kinematics of CLR species for each galaxy will depend on the AGN properties: photoionizing flux from the accretion disk, outflow dynamics and collimation to generate shocks, and secondary X-rays produced by those shocks.

Assuming a uniform ISM, the [Fe II]/Brγ and [Si VI]/Brγ ratios plot the relative ionizing conditions for those species. Figure 26 plots the flux ratio of [Fe II] (1644 nm), H₂, and [Si VI] to Brγ. This shows that [Fe II] becomes relatively stronger toward the end and around the edges of the outflow. The [Si VI] is more concentrated near the AGN; however, it is present the full length of the outflow. The H₂ emission is centrally concentrated, but as we will see, it is kinematically disassociated from the outflow and ionized species. This will be explored in Sections 3.4.2 and 4.1.

4.6. The Star-forming Ring

The stellar age in the SF ring was determined from the Paβ EW, using the STARBURST99 models of Leitherer et al. (1999). These produce EW data for a range of metallicities and initial mass functions, all showing a static EW until about 3–5 Myr, and then a rapid decrease to about 10 Myr. Three locations in the ring, but out of the line of the outflows, were used, as shown in the top right panel of Figure 11 (circles); the EW was averaged within a radius of 3 pixels. These values were in the range 0.16–0.42 nm, which is equivalent to 7.4–8.4 Myr for the model with solar metallicity, a mass cutoff of 100 M☉, and an initial mass function slope of 2.35.

We can obtain a measure of the SF rate in the ring, using the Hα flux and the Kennicutt et al. (2009) relationship. We estimate the true, non-AGN-contaminated flux by selecting pixels with an AGN mixing ratio of <50%. We also select pixels where the Balmer-decrement-derived extinction is less than 4 mag, as the derived extinction is probably uncertain over that value. We then correct the flux at each pixel by the formula

\[ F(H\alpha)_C = F(H\alpha)_O \times 10^{0.4 \lambda k(\lambda)}, \]  

where \( F(H\alpha)_O \) and \( F(H\alpha)_C \) are the observed and corrected Hα fluxes, respectively, and \( k(\lambda) = A_\lambda/A_\gamma \). For Hα, \( k(\lambda) = 0.818 \), from the Cardelli et al. (1989) formulation.

Figure 28 show the Hα observed and corrected fluxes and the extinction map for the nuclear region (10″—note the scale). The average Hα flux for the selected pixels is \( 7.41 \times 10^{-16} \) erg cm^{-2} s^{-1} (\( L(H\alpha) = 1.5 \times 10^{39} \) erg s^{-1} at 41.1 Mpc), which gives a star formation rate of \( \sim 0.029 \) M☉ yr^{-1} arcsec^{-2} (0″/2 pix^{-1}). We can estimate the SF ring size by assuming an annular geometry around the nucleus; this is measured at \( \sim 3″/2 \) for the inner and 7″ for the outer radii. The total star formation rate over the ring is thus \( \sim 3.5 \) M☉ yr^{-1}.

We can also estimate the stellar ages from the Hβ EW, using the same method as for Paβ above. The Hβ EWs for the flux peaks around the ring (interpreted as individual star clusters) are in the range of 0.78–1.43 nm; this equates to stellar ages of 6.15–6.45 Myr (broadly compatible with the values derived from Hβ).

If the total VLA 6 cm flux, as shown in Figure 3 (bottom left panel), is summed on the NE sector of the circle (since the jet interferes with the SW sector), a value of \( \sim 70 \) mJy is obtained. At the distance of 41.1 Mpc, this translates to a luminosity of \( \sim 1.4 \times 10^{22} \) W Hz^{-1}. Using the indicator of Condon (1992) (their Equation (18)) where \( \nu = 5 \) GHz and \( \alpha = -0.8 \), this is equivalent to an SN rate of \( \sim 0.4 \) yr^{-1}; this value may well be high, as the jet emission may be contributing to the measured flux. The individual SNR luminosities are \( \sim 4.4 \times 10^{20} \) W m^{-2}; again, the unmasked jet emission will contribute some of this luminosity. This can be compared to the SNRs in M82, which have luminosities in the range of \( (0.02–1.7) \times 10^{20} \) W m^{-2} (Muxlow et al. 1994). The spacing of the SNRs is reminiscent of the nuclear rings of star clusters; examples are cited in Brandl et al. (2012) and Pan et al. (2013) for NGC 7552 and in Böker et al. (2008) for five nearby spiral galaxies.

5. Conclusion

We have examined the nuclear region of NGC 5728 using data at multiple wavelengths and methods (X-ray, optical, and NIR IFU spectra, and radio), revealing a highly complex object showing gas with multiple morphologies and excitation modes,
driven by a powerful AGN. We have presented and analyzed emission-line morphologies and excitation diagnostics, estimating stellar populations and ages and obscuration from continuum emission and line ratios, and also determined gas column densities.

In summary, the nuclear region has the following features:

1. Dust lanes and spiraling filaments feed the nucleus, as revealed by the HST structure maps.
2. An SF ring with a stellar age of 7.4–8.4 Myr, with a star formation rate $\simeq 3.5 M_\odot$ yr$^{-1}$.
3. A one-sided radio jet, impacting on the ISM at about 200 pc from the nucleus, combined with radio emission from the SN remnants in the SF ring.
4. Biconal ionization, traced by gas emission of H II, [Fe II], and [Si VI], extending off the edges of the observed field. MUSE [O III] data show that the full extent of the cones is over 2.5 kpc from the nucleus.
5. The AGN and BLR are hidden by a dust bar of size $64 \times 28$ pc, with up to 19 mag of visual extinction, with an estimated dust temperature at the nuclear position of $\sim 870$ K. Extinction maps derived from both hydrogen recombination and [Fe II] emission lines show similar structures, with some indication that [Fe II]-derived extinction does not probe the full depth of the ionization cones. There is some evidence for dust being sublimated in the outflows, reducing the extinction. This is supported by extinction measures derived from MUSE H$\alpha$/H$\beta$ emission, which show a decreased absorption in the ionization cones.
6. An extended CLR traced by [Si VI], out to $\sim 300$ pc from the nucleus. This is excited by direct photoionization from the AGN, plus shocks from the high-velocity outflows. Higher-ionization species ([Ca VIII] and [S IX]) are closely confined around the AGN.
7. Line ratio active galaxy diagnostics show mostly AGN-type activity, with small regions of LINER and TO modes at the peripheries of the outflows and where the dusty torus obscures the direct photoionization from the black hole. MUSE optical diagnostics (BPT diagrams) show a clean star formation/AGN mixing sequence.
8. The H$_2$ gas is dynamically and spatially independent of the outflows, concentrated in an equatorial disk in the SF ring, but also showing entrainment along the sides of the bicone. The warm H$_2$ has a mass of 960 $M_\odot$ in the central 600 $\times$ 600 pc, with an estimated $6 \times 10^{6}$ $M_\odot$ of cold H$_2$ in the field of view. Line ratio diagnostics indicate that the gas is excited by thermal processes (shocks and radiative heating of gas masses) to temperatures in the range of 1400–2100 K, with an increased ratio of fluorescent excitation toward the SF ring.
9. With 100 pc of the nucleus, the ionized gas mass (derived from the Br$\gamma$ emission) is $8 \times 10^{5}$ $M_\odot$, and the cold H I gas mass (from extinction calculations) is $4.9 \times 10^{6}$ $M_\odot$; however, this could be underestimated owing to dust sublimation in the outflows.

To understand the complex nature of AGNs, their associated nuclear gas and stars must be studied at the highest resolution possible using multimessenger observations. ALMA observations, revealing the cool dust component, would add materially to the physical map we have constructed here.

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Facilities: VLT:Yepun (SINFONI, MUSE).
Software: TinyTim (Krist et al. 2011), QFsView (Ott 2012), gasgano (ESO 2012).

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