Powerful multiphase outflows in the central region of Cygnus A

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ABSTRACT
We use Gemini Near-Infrared Integral Field Spectrograph (NIFS) observations of the inner 3.5 × 3.5 kpc² of the radio galaxy Cygnus A to map the gas excitation and kinematics at a spatial resolution of 200 pc. The emission of the ionised gas shows a biconical morphology, with half-opening angle of 45° and oriented along the position angle of the radio jet. Coronal line emission is seen within the cone, up to 1.75 kpc from the nucleus, with higher ionisation gas observed in the easterly side. The H₂ and [Fe ii] emission lines are consistent with excitation by the central AGN, with some contribution of shocks to the southwest of the nucleus. The gas visual extinction and electron density are larger than those from optical-based measurements, consistent with the fact that near-IR observations penetrate deeply into the gas emission structure, probing denser and more obscured regions. The gas kinematics shows two components: (i) a rotating disc with kinematic position angle of Ψ₀ = 21° ± 2°, seen both in ionised and molecular gas, and (ii) outflows with velocities of up to 600 km s⁻¹ observed within the ionisation cone in ionised gas and restricted to inner 0.5 arcsec in molecular gas. The mass outflow rate in ionised gas is in the range ∼100 − 280 M⊙ yr⁻¹ and the kinetic power of the outflow corresponds to 0.3–3.3 per cent of the AGN bolometric luminosity, indicating that the outflows in Cygnus A may be effective in suppressing star formation.

Key words: galaxies: active – galaxies: jets – galaxies: kinematics and dynamics – galaxies: individual: Cygnus A – galaxies: ISM – galaxies: evolution

1 INTRODUCTION
Feedback from Active Galactic Nuclei (AGN) is a critical transformation mechanism of galaxies from star-forming to quiescent, coupling the growth of the central supermassive black holes (SMBHs) and their host galaxies (e.g. Cattaneo et al. 2009; Alexander & Hickox 2012; Conselice 2014; Harrison 2017) and being responsible for the correlation between the mass of the SMBH and the mass of the galaxy bulge (e.g. Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000; Ferrarese & Ford 2005). AGN feedback is a strong function of luminosity and high-luminosity AGN inject enough energy into the surrounding medium so that the wind can overcome the inertia of the gas in the galactic potential (Harrison et al. 2018). Cygnus A is one of the most powerful AGN in the local Universe and an ideal laboratory to investigate the effect of the AGN on the host galaxy, by mapping the gas kinematics and emission structure in the nuclear region in details.

Cygnus A is a narrow-line radio galaxy (Osterbrock & Miller 1975), its redshift is z = 0.0561 (Owen et al. 1997) and hosts the most powerful radio-emitting AGN at z < 0.1 (e.g. Carilli & Barthel 1996). Cygnus A shows a radio jet to the northwest and a counter jet to the southeast of the nucleus, seen from sub-pc scales to up to 70 kpc from the nucleus, with superb radio lobes and strong hot-spots (Figure 1, Perley et al. 1984b; Linfield 1985; Carilli & Barthel 1996). The jet and hot-spots are also seen in X-rays, together with a giant cavity surrounding the galaxy, carved by the jet (Figure 1, Wilson et al. 2006a,b; Snios et al. 2018) produced by an obscured AGN as indicated by the detection of absorbed, power-law X-ray emission (e.g. Ueno et al. 1994; Young et al. 2002).

In the optical, Cygnus A presents a complex dust bipolar structure and a kpc-scale ionisation bicone along the southeast-northwest direction, well aligned with the radio jet (Figure 1, Carilli et al. 1989; Jackson et al. 1994, 1996, 1998). The nucleus is highly obscured in the optical due to dust along the line of sight (e.g. Vestergaard & Barthel 1993), with visual extinction of A_v = 40 – 150 mag as derived using mid (Imanishi & Ueno 2000; Ramírez et al. 2014) and near-IR (Djorgovski et al. 1991; Packham et al. 1998; Tadhunter et al. 1999) observations. Privon et al. (2012) modeled the spectral energy distribution (SED) of Cygnus A from radio wavelengths to the mid-infrared, and found that the mid-infrared emission is consistent with radiation emitted by a dusty torus with size of ~130 pc heated by an AGN with bolometric luminosity of 10^{12} L⊙. Recently, using Jansky Very Large Array

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images at 18-48 GHz, Carilli et al. (2019) reported the detection of an elongated ~500 pc structure, perpendicular to the radio jets and centred on the core, providing a direct evidence of a dusty torus in Cygnus A.

Tadhunter et al. (2003) studied the gas kinematics in the narrow-line region of Cygnus A using optical and near-IR long-slit spectra, obtained with the STIS instrument on the Hubble Space Telescope and the NIRSPEC instrument coupled to the Keck II Telescope, respectively. They found that the kinematics of Pa\(\alpha\), H\(\gamma\)2.1218\(\mu\)m and [O\(\text{iii}\)]\(\lambda\)5007 show a rotation pattern across the nucleus along a position angle PA\(= 180^\circ\), perpendicularly to the radio jet, while no evidence for rotation along the radio axis is observed. In addition, their data reveal an ionised gas outflow, northwest of the nucleus. Edwards et al. (2009) used optical integral field unit observations of the inner 7.7\(\times\)10.8 arcsec\(^2\) of Cygnus A to map the ionised gas emission structure and kinematics at an angular resolution of 0.7 arcsec. They found that the optical-emission line fluxes (H\(\alpha\), [N\(\text{ii}\)]\(\lambda\)6583 and [O\(\text{iii}\)]\(\lambda\)6583) are consistent with emission of gas photoionised by and AGN in most locations, the flux distributions are more elongated along the northwest-southeast direction, with the highest flux values
observed to the northwest and in the central core. The gas velocity fields show gradients of up to ±200 km s\(^{-1}\) along the northeast-southwest direction, consistent with rotation, while the line widths are large (σ ≈ 300 km s\(^{-1}\)) in regions co-spatial with the central radio core and to the west of the nucleus, suggesting an interaction between the radio jet and the interstellar medium (Edwards et al. 2009).

The near-IR nuclear spectrum of Cygnus A presents emission lines produced in a wide range of gas phases, including lines from molecular, low and high-ionisation gas (Wilman et al. 2000; McGregor et al. 2007). Gemini Near-Infrared Integral Field Spectrograph (NIFS) observations show that the emission structure of the ionised gas (traced by [Si\(\text{X}\)]1.4305 \(\mu\)m, [Fe\(\text{II}\)]1.6440 \(\mu\)m, and [H\(\text{II}\)]1.5331 \(\mu\)m, [Fe\(\text{II}\)]1.6440 \(\mu\)m, Pao, [S\(\text{X}\)]1.8921 \(\mu\)m, Br\(\gamma\), H\(\text{II}\)1.9576 \(\mu\)m, [Si\(\text{VI}\)]1.9630 \(\mu\)m, H\(\text{II}\)2.034 \(\mu\)m, H\(\text{II}\)2.1218 \(\mu\)m, Br\(\gamma\), H\(\text{II}\)2.2477 \(\mu\)m, and H\(\text{II}\)2.2477 \(\mu\)m), and measure their physical properties. The contribution of the underlying continuum is fitted by a third order polynomial.

In some locations, the line profiles are complex, presenting more than one kinematic component, and are not well reproduced by a single Gaussian. Thus, we fit each emission-line profile by (i) a single-Gaussian curve, (ii) two-Gaussian curves and by (iii) Gauss-Hermite series. Both, the Gauss-Hermite and two-Gaussian are able to reproduce the observed profiles over the whole field-of-view. The H\(\text{II}\), [Fe\(\text{II}\)] and H\(\text{I}\) emission lines trace distinct gas phases. The H\(\text{II}\) traces the hot molecular gas (\(T \approx 20000\)K), the [Fe\(\text{II}\)] emission arises from partially ionized zones, while the H\(\text{I}\) recombination lines are produced in fully ionized gas. Considering that, during the fit, the velocity and velocity dispersion of the components of emission lines from the [Fe\(\text{II}\)], H\(\text{I}\) and H\(\text{II}\) were tied, separately.

Figure 2 shows examples of the fits of the [Si\(\text{X}\)]1.4305 \(\mu\)m (top-left), [Fe\(\text{II}\)]1.6440 \(\mu\)m (top-right), Pao (bottom-left) and H\(\text{II}\)2.1218 \(\mu\)m (bottom-right) line profiles for the nuclear spaxel, corresponding to the location where the lines are the most complex. The line profiles clearly present two kinematic components: a narrow and a broad-blueshifted component. In each panel, the observed profile is shown as a gray dashed line, the fit by a Gauss-Hermite series as a blue dotted line and the two-Gaussian model as a red continuous line. The fluxes of the emission lines obtained by modeling the profiles by

**2 DATA AND MEASUREMENTS**

We analyse archival H, K\text{short} and K-band data obtained with the Gemini Near-Infrared Integral Field Spectrograph (NIFS), under the program GN-2006A-C-11 (PI: McGregor). NIFS has a square field of view of 3×3 arcsec\(^2\), divided into 29 slices with an angular sampling of 0′′103×0′′042 and is optimized to operate with the ALTitude conjugate Adaptive optics for the InfraRed (ALTAIR) instrument (McGregor et al. 2003). The H\(\text{II}\) band observations were done using the H\(\text{I}\) G5604 grating and the JH\_G0602 filter, for the K\text{short} observations the K\text{short}–G5606 grating and the HK\_G0603 filter were used and K-band data were obtained using the K\_G5605 grating and the HK\_G0603 filter. The resulting spectral ranges are 1.476–1.802 \(\mu\)m, 1.906–2.341 \(\mu\)m and 2.009–2.442 \(\mu\)m for the H, K\text{short} and K bands, respectively. The on-source exposure time was 1.5 hours in the H\(\text{II}\) band and 1.75 hours in the K\text{short} and K bands, divided into individual exposures of 900 sec. Preliminary emission-line flux maps were already presented in McGregor et al. (2007), based on these data. The data reduction was accomplished using the NIFS.GEMINI.HARF package, following the standard procedure as described in previous works (e.g Riffel et al. 2008, 2017).

The angular resolution is 0.18′′±0.03 arcsec (corresponding to 210±35 pc at the galaxy) for the K\text{short} and K bands, as measured from the full-width at half maximum (FWHM) of the flux distribution of the standard star. For the H\(\text{II}\) band, the angular resolution 0.16′′±0.03 arcsec (185±35 pc). For both bands, the resulting velocity resolution is 48±5 km s\(^{-1}\), estimated from the FWHM of emission lines of the wavelength calibration lamp spectra. The bottom panel of Fig.1 shows the NIFS H+K band nuclear spectrum of Cygnus A, extracted within the circular aperture with 0′′25 radius. We follow a similar procedure as described in Riffel et al. (2020) and use the IFSCUBE code (Ruschel-Dutra 2020) code to fit the emission-line profiles of [Si\(\text{X}\)]1.4305 \(\mu\)m, [Fe\(\text{II}\)]1.5331 \(\mu\)m, [Fe\(\text{II}\)]1.6440 \(\mu\)m, Pao, [S\(\text{X}\)]1.9201 \(\mu\)m, Br\(\gamma\), H\(\text{II}\)1.9576 \(\mu\)m, [Si\(\text{VI}\)]1.9630 \(\mu\)m, H\(\text{II}\)2.034 \(\mu\)m, H\(\text{II}\)2.1218 \(\mu\)m, Br\(\gamma\), H\(\text{II}\)2.2477 \(\mu\)m, and H\(\text{II}\)2.2477 \(\mu\)m, and measure their physical properties. The contribution of the underlying continuum is fitted by a third order polynomial.
Gauss-Hermite series and by Gaussian curves are consistent with each other, with a standard deviation of the difference between these fluxes smaller than 10 per cent for all considered lines.

3 RESULTS

The near-IR spectra of Cygnus A show strong emission lines, which can be used to map the multiphase gas distribution and kinematics, of the hot molecular gas (traced by the H$_2$ lines), low-ionisation gas (traced by the [FeII] lines and H$\alpha$ recombination lines) and coronal gas (traced by high-ionisation emission-lines species, such as [Si\textsc{x}]1.4305 $\mu$m and [Si\textsc{vi}]1.9630 $\mu$m).

3.1 Results from the Gauss-Hermite fits

Figure 3 shows maps for the fluxes (first column), velocities (second column), $\sigma$ (third column), $h_3$ (forth column) and $h_4$ moments (fifth column) obtained from the fits of the observed line profiles by Gauss-Hermite series. We present these maps for the [Si\textsc{x}]1.4305 $\mu$m, [FeII]1.6440 $\mu$m, Pa$\alpha$, [Si\textsc{vi}]1.9630 $\mu$m and H$\alpha$2.1218 $\mu$m emission lines, which present the highest signal-to-noise (S/N) ratio among their species. Gray regions in these maps represent masked locations, where the lines are not detected above 3$\sigma$ continuum level.

The emission-line flux distributions (first column of Fig. 3) presented here are similar to those shown in McGregor et al. (2007), obtained by direct integration of the line profiles within a spectral window of $\pm$500 km s$^{-1}$, but the maps presented by these authors are noisier than ours due to the different measurement method. The flux maps for [Si\textsc{x}]1.4305 $\mu$m, Pa$\alpha$ and [Si\textsc{vi}]1.9630 $\mu$m show a well defined ‘X-shaped’ emission morphology in the highest flux levels. This structure seems to delineate the walls of a bicone oriented along the position angle (PA) of the radio jet (PA$\approx$284$^\circ$, e.g. Fig 1 and Carilli & Barthel 1996), with an opening angle of $\approx$90$^\circ$.

The orientation of the radio jet is represented by the green line in Fig. 3 and the blue lines delineate the bi-conical emission structure. The [FeII]1.6440 $\mu$m shows a more rounded and centrally peaked flux distribution. Some collimated emission is also observed, mainly to the north-west of the nucleus. The H$_2$ emission structure is distinct from that of the ionised gas. The highest flux levels are seen approximately along the north-south direction, outside the bi-conical emission structure observed in the ionised gas.

The velocity maps (second column of Fig. 3) of all emission lines show redshifts to the north-northeast and blueshifts to the south-southwest of the nucleus. The velocity values range from $-$170 to 170 km s$^{-1}$ relative to the systemic velocity of the galaxy of $V_s = 16800$ km s$^{-1}$, obtained by fitting the H$_2$ velocity field by a rotating disc model (see Sec. 4.5). Some differences are seen between the maps for the ionised gas and the H$_2$ velocity field. For instance, the velocity fields for the ionised gas show the highest redshifts further east ($\Delta\alpha, \Delta\delta \approx (0.5$ arcsec, +0.3 arcsec) of the region with the highest velocities in the H$_2$ map, which presents the largest velocity gradient in the direction perpendicular to the radio jet.

The $\sigma$ maps are presented in the third column of Fig. 3 and show a wide range of values, from $\sim$50 to 350 km s$^{-1}$.

These maps were corrected for the instrumental broadening of $\sigma_{\text{inst}} = 20$ km s$^{-1}$. The lowest $\sigma$ values are observed at distances $r \lesssim 0.5$ arcsec from the nucleus, mainly to south-southeast and northwest of the nucleus, while the highest values are observed at the nucleus, to northeast and southwest of it. Overall, the H$_2$ shows the smallest mean $\sigma$ values and the highest values are observed for the [FeII].

The maps for the $h_3$ Gauss-Hermite moment are shown in the forth column of Fig. 3. This parameter measures asymmetric deviation from a Gaussian profile, such as blue ($h_3 < 0$) or red wings ($h_3 > 0$). In most locations, the observed values of $h_3$ are in the range from $-$0.1 to 0.1. The lowest values ($\sim$ $-$0.2) are seen at the nucleus and to the north-northwest, regions where emission-line profiles clearly present a blue wing (e.g. Fig. 2). The highest values ($\sim +0.2$) are observed mainly to the east of the nucleus, indicating red wings on the line profiles.

The $h_4$ moment measures symmetric deviation from a Gaussian profile, i.e. it quantifies the peakiness of the profile, with $h_4 < 0$ for a broader and $h_4 > 0$ for a more peaked profile than a Gaussian (e.g. Riffel 2010). The lowest values in the $h_4$ maps (fifth column of Fig. 3) for Cygnus A are observed close to the nucleus, co-spatially with the highest $\sigma$ values, indicating that the line profiles are broader than a Gaussian.

3.2 Emission-line flux ratios

We estimate the visual extinction ($A_v$) using the Pa$\alpha$/Br$\gamma$ emission-line flux ratio, calculated using the fluxes measured from the modeling of the line profiles by Gauss-Hermite series. The $A_v$ can be estimated as follows (e.g. Calzetti et al. 2000; Domínguez et al. 2013; Riffel et al. 2021c)

$$A_v = \frac{2.5}{(f_{\lambda}(\text{Br}\gamma) - f_{\lambda}(\text{Pa}\alpha))} \log \left[ \frac{(F_{\text{Pa}\alpha}/F_{\text{Br}\gamma})_{\text{obs}}}{(F_{\text{Pa}\alpha}/F_{\text{Br}\gamma})_{\text{int}}} \right],$$

where $f_{\lambda}(\text{Pa}\alpha)$ and $f_{\lambda}(\text{Br}\gamma)$ are the reddening curve values at the Pa$\alpha$ and Br$\gamma$ wavelengths, $(F_{\text{Pa}\alpha}/F_{\text{Br}\gamma})_{\text{obs}}$ is the observed Pa$\alpha$/Br$\gamma$ emission-line flux ratio in each spaxel and $(F_{\text{Pa}\alpha}/F_{\text{Br}\gamma})_{\text{int}} = 12.4$ is the theoretical Pa$\alpha$/Br$\gamma$ intensity ratio, assuming the Case B H$\alpha$ recombination an electron temperature of $T_e = 20 000$ K (a typical value for the narrow line region, e.g. Revalski et al. 2018a,b; Riffel et al. 2021b) at the low-density limit (Osterbrock & Ferland 2006). Using the extinction law of Cardelli et al. (1989) we obtain $f_{\lambda}(\text{Pa}\alpha) = 0.147$ and $f_{\lambda}(\text{Br}\gamma) = 0.116$, and thus

$$A_v = -80.6 \log \left[ \frac{(F_{\text{Pa}\alpha}/F_{\text{Br}\gamma})_{\text{obs}}}{12.4} \right].$$

The $A_v$ map for Cygnus A is shown in the left panel of Fig. 4. High $A_v$ values are observed in most location, reaching values of up to 20 mag to the northwest of the nucleus. The mean value and standard deviation of the mean are 12.5 mag and 6.3 mag, respectively.

The [FeII]1.5330 $\mu$m/[FeII]1.6440 $\mu$m emission-line ratio can be used to estimate the electron density, $N_e$ (e.g. Storchi-Bergmann et al. 2010a). We correct the line fluxes by extinction using the $A_v$ values measured for each spaxel and the extinction law of Cardelli et al. (1989) and derive $N_e$ using the PyNEB routine (Luridiana et al. 2015), assuming an electron temperature of $T_e = 20 000$ K (e.g., Revalski et al.
Figure 3. Maps produced by modeling the emission-line profiles by Gauss-Hermite series. Each row shows the flux, velocity, $\sigma$, $h_3$ and $h_4$ maps for the emission line identified at the title of each panel. The gray regions correspond to locations where the corresponding emission line is not detected above 3$\sigma$ level of the continuum noise. The central cross marks the position of the peak of the K-band continuum. The green dashed line overplotted in the flux maps shows the orientation of the radio jet (Carilli & Barthel 1996) and the blue continuous lines overlaid to the [Si\textsc{vi}] and H$_2$ flux maps represent the bi-conical structure that delineates the highest flux levels observed in emission lines from the ionised gas. The colour bars show the line fluxes in logarithmic units of ergs$^{-1}$cm$^{-2}$ of each spaxel and the velocity and $\sigma$ in km s$^{-1}$. In all panels north is up and east is to the left.

The emission-line intensity ratio maps shown in Fig. 4 were constructed after correcting the fluxes by extinction using the $A_v$ values measured for each spaxel and the extinction law of Cardelli et al. (1989). These maps are useful to investigate the gas excitation (e.g. Reunanen et al. 2002; Rodríguez-Ardila et al. 2004; Riffel et al. 2013, 2021a). The excitation mechanisms of the H$_2$ and [Fe\textsc{ii}] near-IR lines can be investigated using the [Fe\textsc{ii}]1.6440 $\mu$m/Pa$\alpha$ and H$_2$2.1218 $\mu$m/Br$\gamma$ flux ratios. The highest values of [Fe\textsc{ii}]/Pa$\alpha$ are observed at the nucleus and to the southwest, while the smallest ratios are seen mainly at distances larger than 0.5 arcsec from the nucleus. The H$_2$/Br$\gamma$ map presents the lowest values within the bi-conical structure seen in the flux distributions of the ionised gas emission lines, while the highest values are observed approximately perpendicularly to this structure. The [Si\textsc{x}i]1.4305 $\mu$m and [Si\textsc{vi}]1.19630 $\mu$m are coronal lines with ionisation potentials of 351.1 and 166.8 eV, respectively (Rodríguez-Ardila et al. 2011) and thus they are tracers of the high ionisation gas. The [Si\textsc{vi}]/Pa$\alpha$ ratio map presents the
highest values (of up to 1.0) to the southeast and the smallest values (≈0.2) are observed to the northwest of the nucleus. A similar behaviour is observed in the [Si x] 1.4305 Å/Pα map, with values of up to ~0.5 observed to the southeast of the nucleus and smaller values to the northwest of it.

### 3.3 Results from the Gaussian fits

All the emission lines present in the Cygnus A H+K spectra show a broad and blueshifted component observed in some locations, particularly strong in the central region. In Figs. 5 and 6 we show the flux (left panels), centroid velocity (middle panels) and velocity dispersion (right panels) maps for the narrow (top) and broad (bottom) components of Pα and H2 2.1218 Å/Brγ flux ratios. These lines were chosen because they present the highest S/N ratios among the lines produced by the ionised and molecular gas, respectively. We mask out spaxels where the amplitude of the fitted components are smaller than 3σ level of the continuum noise, next to the considered line. In locations where the broad component is not detected, we fit the corresponding line profile by a single Gaussian function, representative of the narrow component.

The maps for the narrow component are similar to those shown in Fig. 3, obtained by fitting the line profiles by Gaussian-Hermite series. The flux distribution for the Pα broad component shows a linear structure to the northwest of the nucleus, extending to up to 1.5 arcsec (1.75 kpc) from it. The peak of emission is seen at the galaxy’s nucleus. A similar extended structure is also seen in [Fe ii] 1.6440 μm, while for emission lines from highly ionised gas (e.g. [Si x] 1.4305 μm) only the nuclear emission is detected above the 3σ level of the continuum noise. The Pα broad component is blueshifted, with typical velocities of 400–600 km s\(^{-1}\) relative to the systemic velocity of the galaxy, and presents σ = 600 – 720 km s\(^{-1}\). The broad component in H2 2.1218 Å is detected only at the nucleus and has a smaller centroid velocity and velocity dispersion than those of Pα. This component is blueshifted by ~300 km s\(^{-1}\) and has a σ ≈ 280 km s\(^{-1}\).

### 4 DISCUSSION

#### 4.1 Gas extinction

A complex dust structure in the inner few kpc of Cygnus A is observed in optical broad band images (e.g. Carilli et al. 1989; Jackson et al. 1994, 1996, 1998) and the nuclear visual extinction has been measured using optical (e.g. Edwards et al. 2009), near-IR (Djorgovski et al. 1991; Packham et al. 1998; Tadhunter et al. 1999; Wilman et al. 2000) and mid-IR (Imanishi & Ueno 2000; Ramirez et al. 2014) spectroscopy. These studies show that the visual extinction (A\(_ν\)) values based on optical emission lines are smaller than those derived using infrared lines. For instance, Tadhunter et al. (2000) found A\(_ν\) = 9 mag based on the Brγ/Pα ratio for the nucleus of Cygnus A. Our extinction map (Fig. 4) shows values of up to 20 mag, with an average value of 12.5 ± 6.3 mag. Edwards et al. (2009) presented an extinction map of the inner 4.5 × 4.5 arcsec\(^2\) region of Cygnus A, based on the Hα/Hβ flux line ratio observed using integral field spectroscopy at an angular resolution of 0.7 arcsec. Their map, although noisy, show the highest value of A\(_ν\) ~ 3 mag along the northwest-southeast direction. Our map shows a similar behaviour, but with overall higher values, with the highest gas extinction seen along the walls of the ionisation cone.

As already discussed in Wilman et al. (2000), a likely expla-
Figure 5. Flux (left), centroid velocity (middle) and velocity dispersion (right) maps for the narrow (top panels) and broad (bottom panels) for Paα. The green dashed line and the blue continuous lines overplotted in the flux map for the broad component show the orientation of the radio jet (Carilli & Barthel 1996) the bi-conical structure seen in the ionised gas emission, respectively. The colour bars show the fluxes in logarithmic units of erg s$^{-1}$ cm$^{-2}$ of each spaxel and the velocity and σ in km s$^{-1}$. In all panels north is up and east is to the left.

Figure 6. Same as Fig. 5, but for the H2 2.1218 μm emission line.

The extinction in the near-IR is lower than in the optical, and thus, infrared observations can penetrate more deeply into the gas emission structure and probe more obscured regions. Indeed, higher $A_V$ values based on near-IR emission lines than those from optical emission lines are commonly reported in the literature for nearby galaxies (e.g. Martins et al. 2013).
4.2 Gas Density

The [Fe ii] near-IR emission lines originate in partially ionised zones, which can be produced by X-rays (Simpson et al. 1996) or shocks (Forbes & Ward 1993), in the central region of galaxies. Similarly, the $\text{[S ii]}\lambda 6717,6731$ emission lines also originate in partially ionised zones, but the critical density for the $\text{[S ii]}$ lines $(2.5 \times 10^4 \text{ cm}^{-3})$ is smaller than that for the [Fe ii] lines $(\sim 10^5 \text{ cm}^{-3};$ Storchi-Bergmann et al. 2009). For Cygnus A, the average electron density in the [Fe ii] emission region is $N_e = 7900 \text{ cm}^{-3}$ (Fig. 4), above the critical density for the [S ii].

Tadhunter et al. (1994) reported values of $1/(\text{[S ii]}\lambda 6717/\text{[S ii]}\lambda 6731$ $(1.4$ using long-slit slit observations along two position angles, PA$=-15^\circ$ and PA$=105^\circ$, covering the inner 3 arcsec of Cygnus A. These values correspond to densities of $25 \text{ cm}^{-3}$ $(N_e \approx 915 \text{ cm}^{-3}$ as obtained using the PyNeb routine (Luridiana et al. 2015) and assuming an electron temperature of $T_e = 20000 \text{ K}$. Using the fluxes of the [S ii] doublet obtained from the nuclear spectrum of Cygnus A presented by Torrealba et al. (2012) and adopting the same procedure, the resulting density is $N_e \approx 525 \text{ cm}^{-3}$. Thus, the $N_e$ values in the [Fe ii] emission region is about 15 times larger than that obtained from [S ii] lines.

The densities derived from the [S ii] doublet seem to underestimate the density of ionised outflows in the narrow-line region of luminous Seyfert galaxies by up to two orders of magnitude, because the assumption that the [S ii]-based electron density traces the hydrogen density is invalid, as the [S ii] emission arises from partially ionised zones (Baron & Netzer 2019; Davies et al. 2020). An alternative to derive the density of the ionised gas is by using the optical $\lambda \lambda 4711,4740$ emission lines, which trace denser gas phases than the [S ii] line ratio. Measuring the fluxes of these lines from the nuclear spectrum of Torrealba et al. (2012), using the PyNeb routine and adopting $T_e = 20000 \text{ K}$, we derive $N_e \approx 4450 \text{ cm}^{-3}$, which is roughly half the value obtained from the [Fe ii] lines. A possible explanation for the large discrepancy between the $N_e$ values derived from optical emission lines and from the near-IR [Fe ii] is that, as mentioned above, the near-IR observations are able to probe dustier gas clouds. These clouds are likely more directly illuminated by the AGN radiation field, and possibly compressed by AGN winds, increasing the gas density.

4.3 Flux distributions

Ground based and Hubble Space Telescope narrow-band images of Cygnus A revealed a well defined bipolar emission structure in the inner $\sim3$ kpc (e.g. Pierce & Stockton 1986; Jackson et al. 1996, 1998), which can be described as having a biconical or parabolic/hourglass morphology. This emission structure is well aligned with the orientation of the radio jet, with a position angle of $284^\circ$ on the sky (e.g. Perley et al. 1984b; Carilli & Barthel 1996); it may result from a combination of mechanical excitation of the gas in shocked regions and photoionisation by a hidden quasar like nucleus (e.g. Jackson et al. 1996). Similar hourglass morphologies have been observed for the narrow-line region of closer Seyfert galaxies, as for instance in NGC 4151 (e.g. Storchi-Bergmann et al. 2010a) and NGC 1068 (e.g. Barbosa et al. 2014).

The broad-band K continuum image of the central region of Cygnus A, obtained with the Keck II Telescope at an angular resolution of 0.05 arcsec, also clearly show the ionisation/scattering bicone and reveals an unresolved nucleus at the cone apex (Canalizo et al. 2003). The NIFS K-band continuum image, shown in Fig. 1, presents a similar morphology.

Preliminary flux maps from the NIFS data analysed here, obtained by integrating the line profiles over $\pm 500 \text{ km s}^{-1}$ equivalent waveband, were already presented in McGregor et al. (2007). They presented flux maps for the $H_2$ $\lambda \lambda 1218 \mu\text{m}$, [Fe ii] $\lambda \lambda 6440 \mu\text{m}$, Paα, [Si x] $\lambda \lambda 1305 \mu\text{m}$ and [Si vi] $\lambda 9630 \mu\text{m}$. Our flux maps (left panels of Fig. 3) are well consistent with theirs, but less noisy, as their maps were constructed by direct integration of the line profiles and thus more sensitive to the continuum noise. The biconical morphology is clearly seen in the flux maps for the emission lines from the ionised gas. The gas emission seems to be tracing the walls of the cones, as seen in the K-band continuum image, delineating an "X-shaped" emission structure. The [Si vi]/Paα and [Si x]/Paα intensity ratio maps show the highest values in the easterly cone, indicating that the ionisation parameter of the gas in this side is higher than that in the westerly cone. A possible interpretation for this behaviour is given by McGregor et al. (2007), in which the easterly cone is matter bounded and in the westerly cone dense matter seems to be obtruding into the cone.

The [Fe ii] $\lambda 6440 \mu\text{m}$ shows a more round flux distribution than those of lines from other ionised species, and the highest [Fe ii]/Paα values are observed at the nucleus and along the northeast-southwest direction. These higher [Fe ii]/Paα values outside the ionisation cone may be tracing emission from shock-ionised gas produced by nuclear outflows or by the interaction of the radio jet with the gas of the disc (e.g. Riffel et al. 2014, 2021b; Lena et al. 2015; Couto et al. 2016; Ventura et al. 2020), as shocks can be easily observed outside the ionisation cones, where the AGN radiation field is shielded by the nuclear dusty torus (Zakamska & Greene 2014; Riffel et al. 2021b).

The $H_2$ flux distribution (bottom-left panel of Fig. 3) is distinct from those of the ionised gas. Most of the $H_2$ emission is seen from locations outside the ionisation cone, extending along the north-south direction. The $H_2$ seems to be tracing the emission of gas along the major axis of the rotation disc, previously reported using near-IR (Tadhunter et al. 2003) and optical observations (Edwards et al. 2009).

4.4 The [Fe ii] and $H_2$ emission

Figure 7 shows the [Fe ii] $\lambda 6440 \mu\text{m}$/Paα vs. $H_2\lambda 1218 \mu\text{m}$/Brγ diagnostic diagram for Cygnus A and the corresponding excitation map, which are useful to investigate the origin of the [Fe ii] and $H_2$ emission lines (e.g. Rodriguez-Ardila et al. 2005; Riffel et al. 2013; Colina et al. 2015; Riffel et al. 2021a). The lines delineating the star-forming (SF), AGN and high line ratio (HLR) regions are from Riffel et al. (2013), by converting the [Fe ii] $\lambda 2570 \mu\text{m}/Pa\beta$ to [Fe ii] $\lambda 6440 \mu\text{m}$/Paα using Paα/Paβ$=2.0$, assuming the Case B H i recombination, an electron temperature of $T_e = 20000 \text{ K}$, and [Fe ii] $\lambda 6440 \mu\text{m}/[\text{Fe ii}]\lambda 2570 \mu\text{m}=0.785$ (Colina 1993). Colina et al. (2015) used VLT SINFONI observations of 10 luminous infrared galaxies to investigate the two-dimensional ionisation structure and found that in
most galaxies, the [Fe ii] and \( \text{H}_2 \) emission are correlated, while Riffel et al. (2021a) found correlations between the [Fe ii]1.2570\( \mu \text{m}/\text{Pa}\beta \) and \( \text{H}_2 \).21218\( \mu \text{m}/\text{Br}\gamma \) line ratios in 3 of 5 Seyfert galaxies with extended emission, using NIFS observations. In addition, Riffel et al. (2021a) found that the HLR region in Seyfert galaxies is likely produced by shock excitation, as indicated by a correlation between the line ratios and widths. For Cygnus A, we find that all spaxels are excited, as indicated by a correlation between the line ratios and the typical AGN ratios observed along the ionisation cone. The HLR region is mostly due to high Fe/\( \text{H}_2 \)/\( \text{Br}\gamma \) ratios, with the vast majority of \( \text{H}_2/\text{Br}\gamma \) being lower than the upper limit for the AGN region of the diagram, but this line ratio can also be increased by shocks (e.g. Storchi-Bergmann et al. 2010a; Riffel et al. 2021a). Thus, the [Fe ii] emission in the HLR region is likely produced by shocks, as already discussed above. Alternatively, the HLR region could be produced by an enhancement of the Fe/O abundance as suggested by photoionisation models (e.g. Dors et al. 2012).

In Fig. 8, we present the \( \text{H}_2 \).2–1 S(1)2.477\( \mu \text{m} \)/1–0 S(1)2.1218\( \mu \text{m} \) vs. 1–0 S(2)2.0338\( \mu \text{m} \)/1–0 S(0)2.2235\( \mu \text{m} \) diagram for Cygnus A, which can be used to investigate the excitation mechanisms of the \( \text{H}_2 \) emission lines. The small points show the ratios for each spaxel and the black square shows the mean ratios, with the error bars corresponding to the standard deviations of each ratio. The observed ratios can be compared to different model predictions. The black dashed curve represents the predicted ratios for an isothermal and uniform density gas distribution with temperatures in the range 1000 – 4000K. The purple and gray diamonds represent the predictions of shock models of Kwan et al. (1977) and Smith (1995), respectively. The filled and open brown stars are the predictions from the thermal X-ray models of Draine & Woods (1990) and Lepp & McCray (1983), respectively. The magenta polygons show the regions covered by the AGN photoionisation models of Dors et al. (2012). The range of ratios predicted by the non-thermal UV excitation models of Black & van Dishoeck (1987) is shown as an orange polygon. The cyan rectangle delineates the predictions from the thermal UV excitation models of Sternberg & Dalgarno (1989).

As seen in Fig. 8, for Cygnus A, most of the points in the \( \text{H}_2 \).2–1 S(1)2.477\( \mu \text{m} \)/1–0 S(1)2.1218\( \mu \text{m} \) vs. 1–0 S(2)2.0338\( \mu \text{m} \)/1–0 S(0)2.2235\( \mu \text{m} \) diagram lie close to the shock and X-ray excitation models predictions. This result, along with the fact that there are no points in the SF region of Figure 7, indicates that \( \text{H}_2 \) near-IR emission in the central region of Cygnus A is produced by thermal processes. The most likely \( \text{H}_2 \) excitation mechanism in Cygnus A are X-rays from the central AGN, as already discussed by Wilman et al. (2000) using long slit spectroscopy and comparing the observed fluxes with the predictions from models of X-ray dissociation regions of Maloney et al. (1996). Some contribution from shocks to the \( \text{H}_2 \) emission can not be discarded, especially to the southwest, where the highest [Fe ii]1.6440\( \mu \text{m} \)/\( \text{Pa}\alpha \) and \( \text{H}_2 \).21218\( \mu \text{m} \)/\( \text{Br}\gamma \) are observed (Riffel et al. 2021a).

4.4.1 The coronal line region

As observed in Fig. 1, the H and K band spectra of Cygnus A present strong emission lines from highly ionisation species, including [Si ix]1.4305\( \mu \text{m} \), [Si vii]1.9201\( \mu \text{m} \), and [Si vi]1.9630\( \mu \text{m} \). The ionisation potentials of the parent ions of these lines are 351.1, 447.1 and 166.8 for Si ix, Si vii and Si vi, respectively (Rodríguez-Ardila et al. 2011). These lines are called coronal lines (CLs), defined as those produced by ions with ionisation potentials above 100\( \text{eV} \).

The origin of the CL emission in AGN is still under debate. The nuclear (~10s pc) CL emission in AGN seems to originate in photoionised gas in the inner edge of the dusty torus (Shields & Oke 1975; Korista & Ferland 1989; Ferguson et al. 1997; Glidden et al. 2016; Rodríguez-Ardila et al. 2011), while photoionisation models fail to reproduce the CL intensities on scales of a few hundred parsec, and shocks play an important role in the production of these lines (Osterbrock & Parker 1965; Rodríguez-Ardila & Fonseca-Faria 2020). A
Figure 8. $H_2$ $2\rightarrow 1\text{S}(1)2.2477\mu m / 1\rightarrow 0\text{S}(1)2.1218\mu m$ vs. $1\rightarrow 0\text{S}(2)2.0338\mu m / 1\rightarrow 0\text{S}(0)2.2335\mu m$ diagnostic diagram for Cygnus A. The small points show the ratios in individual spaxels, where the lines are detected above $3\sigma$ of the continuum noise. The black square with error bars show the mean line ratios with their standard deviations. The other symbols are model predictions (see text).

combination of both processes, shocks and photoionisation, can also occur (e.g. Viegas-Aldrovandi & Contini 1989; Contini & Viegas 2001; Dors et al. 2021).

Near-IR, adaptive optics observations of nearby active galaxies can be used to map the extension of the CL region. Prieto et al. (2005) found extensions of the [Si vii]$2.48\mu m$ from 30 to 200 pc using adaptive optics narrow band images of four nearby Seyfert galaxies, obtained with the ESO/VLT. Müller-Sánchez et al. (2011) found sizes from 8 to 150 pc measured from the [Si vii]$1.9650\mu m$ flux distributions in a sample of seven luminous Seyfert galaxies. Riffel et al. (2021a) used Gemini NIFS data of six nearby luminous Seyfert galaxies and found [Si x]$1.2523\mu m$ extended emission up to 80–185 pc from the nucleus. Recently, Rodríguez-Ardila & Fonseca-Faria (2020) reported highly ionised gas emission (traced by the [Fe vii]$6087\mu m$) to up to 700 pc from the nucleus of the Circinus galaxy, using MUSE/VLT observations.

In Cygnus A, coronal line emission is observed up to the borders of the NIFS field of view (~1.5 arcsec/1.75 kpc) and well aligned with the radio jet, as seen in Fig. 3. To the best of our knowledge, this is the most extended coronal line region reported for active galaxies, using near-IR observations. Similarly to the result found for Circinus by Rodríguez-Ardila & Fonseca-Faria (2020), where the extended coronal emission is likely the remnant of shells inflated by the passage of a radio jet, the extended CL emission in Cygnus A may be originated by shocks produced by the radio jet or nuclear outflows, as a pure photoionisation scenario fails to reproducing the CLs intensities at these scales (e.g. Rodríguez-Ardila et al. 2006; Mazzalay et al. 2013; Rodríguez-Ardila & Fonseca-Faria 2020).

4.5 Kinematics

Previous optical and near-IR spectroscopic observations of the central region of Cygnus A reveal multiple kinematic components, including gas rotation in 100s pc and kpc scales (e.g. Tadhunter et al. 2003; Edwards et al. 2009), ionised gas outflows (e.g. Tadhunter et al. 1994; Wilman et al. 2000; Taylor et al. 2003) and inflows of neutral (Conway & Blanco 1995) and molecular (Bellamy & Tadhunter 2004) hydrogen.

Regarding the near-IR emission lines, for instance, Bellamy & Tadhunter (2004) presented long-slit spectroscopic data along the orientation of the radio jet (PA=105°), obtained with the NIRSPEC spectrograph on the Keck II telescope. They found that the $Pa\alpha$ line in the central aperture (540 pc width) presents a narrow ($\sigma\sim100$ km s$^{-1}$) component and a broad ($\sigma\sim320$ km s$^{-1}$) component, while at 1.880 kpc northwest of the nucleus, two components narrow components with $\sigma\sim150$ km s$^{-1}$ are observed, one blueshifted by $\sim240$ km s$^{-1}$ and the other redshifted by $\sim150$ km s$^{-1}$, relative to the rest frame of the galaxy. Our NIFS data reveal a broader blueshifted component, seen not only in the nucleus, but extending to northwest of the jet (Fig. 5). A similar component is seen in [Fe ii]$1.6440\mu m$, while for emission lines from highly ionised gas (e.g. [Si x]$1.4305\mu m$) the broad component is detected only in the nucleus. Wilman et al. (2000) also reported a broad component in [Fe ii]$1.6440\mu m$ in the nuclear region of Cygnus A, attributed to shocks produced by the radio jet. For the $H_2$ lines, Bellamy & Tadhunter (2004) detected three kinematic components in the nuclear aperture and two components at distances of 0.8 to 2 kpc from the nucleus to the northwest, along PA=105°. They interpreted the redshifted ($\sim225$ km s$^{-1}$) component as being due to a molecular cloud falling through the nucleus of Cygnus A. The NIFS FoV does not cover the extra-nuclear region discussed by Bellamy & Tadhunter (2004), while at the nucleus the $H_2$ $2.1212\mu m$ emission line is reproduced by two Gaussian components (Fig. 2).

The Gemini NIFS data allow us to spatially resolve the gas emission structure and kinematics in the inner 3.5×3.5 kpc$^2$ of Cygnus A, and thus, further investigate the origin of the molecular and ionised gas emission at the probed scales. The emission-line profiles in all spaxels are reproduced by two-Gaussian functions, a narrow component which is mainly due to emission of gas in a rotating disc and a broad and blueshifted component, produced by outflows. In what follows, we discuss these kinematic components in more details.

4.5.1 The rotating disc

The velocity fields of optical emission lines, obtained from IFU observations of the the inner ~4 kpc of Cygnus A, show a velocity gradient of ±200 km s$^{-1}$ along the northeast-southwest direction, consistent with a rotation disc component (Edwards et al. 2009). Our velocity maps, obtained from the Gauss-Hermite fits (Fig. 3) and from the narrow Gaussian component (Figs. 5 and 6), are similar to those of the optical lines. Deviations from pure rotation are clearly observed in the velocity fields for the ionised gas, as for instance, the redshifts to the east of the nucleus, clearly seen in the velocity fields for the coronal lines. On the other hand, the $H_2$ velocity field is the one that most resembles a pure rotation pattern, with the line of nodes oriented approximately perpendicular to the radio jet.

We fitted the $H_2$ velocity field for the narrow component by an analytical model, assuming that the gas has circular orbits in a plane of the galaxy, with the line-of-sight velocity given by (Bertola et al. 1991):
\[ V_{\text{mod}}(R, \Psi) = V_0 + \frac{AR \cos(\Psi - \Psi_0) \sin(i) \cos^2(i)}{\left\{ R^2 \left[ \sin^2(\Psi - \Psi_0) + \cos^2(\Psi - \Psi_0) \right] + C_0^2 \cos^2(i) \right\}^{p/2}}, \]

where \( R \) is the projected distance to the nucleus with the corresponding position angle \( \Psi \), \( V_0 \) is the galaxy’s systemic velocity, \( A \) is the velocity amplitude, \( i \) is the disc inclination in relation to the plane of the sky (\( i = 0 \) for a face on disc and \( i = 90^\circ \) for an edge on disc), \( \Psi_0 \) is the position angle of the line of nodes, \( p \) measures the slope of the rotation curve, and \( C_0 \) is a concentration parameter. We used the mpfitfun routine (Markwardt 2009) to perform the non-linear least-squares fit.

Figure 9 show the rotating disc model in the left panel and the residual maps (observed velocities – model) for the H\(_{2}\) 2.1218 \( \mu \)m, Pa\(_o\) and [Si\(_x\)] 1.4305 \( \mu \)m emission lines. For the H\(_{2}\), the residuals are small in most locations, with an absolute value of \( \sim 10 \) km s\(^{-1}\) at distances closer than 1 arcsec from the nucleus. Some redshifts of \( \sim 50 \) km s\(^{-1}\) are seen mainly to the northeast, at distances larger than \( \sim 0.8 \) arcsec from the nucleus and within the ionisation cone. The residual maps for the ionised gas show redshifts, mainly within the ionisation cone, with velocities of up to \( \gtrsim 100 \) km s\(^{-1}\) in the southeast cone. These residuals are likely produced by outflows within the ionisation cone, as discussed in the next section.

The resulting best fit parameters are \( V_0 = 16795 \pm 7 \) km s\(^{-1}\), \( A = 195 \pm 14 \) km s\(^{-1}\), \( p = 1.44 \pm 0.06 \), \( \Psi_0 = 21^\circ \pm 2^\circ \), \( C_0 = 0.23 \pm 0.05 \) arcsec, \( i = 30^\circ \pm 7 \) and the kinematical centre is consistent with the location of the continuum peak. If the accretion onto the black hole occurs along a preferred plane, the radio jet is expected to be observed perpendicularly to the inner part of the accretion disc. However, the comparison between the position angles of the jets and those of the dust disc major axes, on scales from tens to hundreds of parsecs, shows that they are not aligned preferentially perpendicular to each other in radio galaxies (e.g. Schmitt et al. 2002). For Cygnus A, we find that the orientation of the line of nodes \( \Psi_0 \) is approximately perpendicular to the orientation of the radio jet, projected in the plane of the sky (PA = 104\(^\circ\) Carilli & Barthel 1996).

### 4.5.2 The multiphase outflows

Previous near-IR long-slit spectroscopic observations of the central region of Cygnus A revealed the presence of blueshifted wings in the emission line profiles from the ionised gas, consistent with outflows in the northwest cone (e.g. Tadhunter et al. 2003). The blueshifted component is clearly detected in our NIFS spectra (Fig. 2), its emission is spatially resolved, and we can further investigate the geometry of the outflows. For the ionised gas, we find that the blueshifted component emission extends from the nucleus to the northwest, up to the borders of the field of view (Fig. 5), while the H\(_{2}\) emission lines show blueshifted wings only in the nucleus in (Fig. 6).

The northwest is the near side of the bicone and the blueshifted component can be attributed to outflows within the northwestern cone. Assuming that the bicone axis and radio jet have the same orientation relative to the line of sight, making an angle of 30\(^\circ\) relative to the plane of the sky (Steenbrugge & Blundell 2008) and a cone half-opening angle of 45\(^\circ\), directly measured from the ionised gas emission-line flux maps (indicated by the blue lines in Figs. 3, 5, 6 and 9), the front wall of the northwestern cone makes an angle of 75\(^\circ\) relative to the plane of the sky (15\(^\circ\) relative the line-of-sight).

The back wall of the northwestern cone is displaced by only 15\(^\circ\), beyond the plane of the sky. Similarly, the front wall of the southeastern cone is in front the plane of the sky, making an angle of 15\(^\circ\) and the back wall of the cone is beyond the plane of the sky and makes an angle of 75\(^\circ\) relative it.

The blue wings detected in the emission lines to the northwest seem to be originated from outflowing gas located close to the front wall of the northwestern cone, with line-of-sight velocities of up to 600 km s\(^{-1}\). The residual velocity maps between the velocity field of the narrow component and the rotating disc model (Fig. 9) for the ionised gas show redshifts to the southeast, with projected velocities of up to \( \sim 150 \) km s\(^{-1}\) inside the ionisation cone. These redshifts are likely produced by outflows inside the southeastern cone. We do not detect the highest velocity components, from the back wall of the southeastern cone, likely because it is obscured by dust, as it is beyond the disc. Some residual redshifts are also seen to the northwest, which may be due to outflows closer to the back wall of the northwestern cone, which is 15\(^\circ\), beyond the plane of the sky. Thus, the kinematics of the ionised gas in the inner 3.5\(\times\)3.5 kpc\(^2\) of Cygnus A is consistent with a rotating disc component, as discussed in previous section, plus a bipolar outflow within the ionisation bicone. The blueshifts detected in H\(_{2}\) could be originated by a compact molecular outflow produced by the interaction of the ionised outflows with the gas in the disc or by a lateral expansion of the dusty torus. Alternatively, the H\(_{2}\) gas could be tracing the outer side of wide-angle winds, as suggested by theoretical studies and numerical simulations of the AGN driven winds (e.g., Silk & Rees 1998; Ramos Almeida & Ricci 2017; Giustini & Proga 2019) and observed for nearby luminous Seyfert galaxies (May & Steiner 2017; May et al. 2020), where the molecular outflows are seen outside the borders of the ionisation cones.

We can use the observed kinematics and geometry of the outflows to roughly estimate the mass outflow rate (\( \dot{M}_{\text{out}} \)), by

\[ \dot{M}_{\text{out}} = 2 m_p N_e v_{\text{out}} f A, \]

where \( m_p \) is the mass of the proton, \( N_e \) the electron density, \( v_{\text{out}} \) is the outflow velocity, \( f \) is the filling factor, \( A \) is the area of the cross section. We consider a circular cross section at 0.5 arcsec from the nucleus, with a radius of \( \sim 600 \) pc for a half-opening cone angle of 45\(^\circ\), \( f = 1 \times 10^{-3} \) (a typical value for the NLR; Martins et al. 2003), \( N_e = 7900 \) cm\(^{-3}\) (the mean value derived in Sec. 4.2), and \( v_{\text{out}} = 600 \) km s\(^{-1}\)/sin(75\(^\circ\)) \( \approx 620 \) km s\(^{-1}\), where 600 km s\(^{-1}\) is the velocity of the blueshifted component (Fig. 5) and 75\(^\circ\) is the angle that the front wall of the northwestern cone makes with the plane of the sky, as discussed above. Under these assumptions and considering a filled cone, we obtain \( \dot{M}_{\text{out}} \approx 280 \dot{M}_\odot \) yr\(^{-1}\). The ionised gas mass outflow rates are usually highly uncertain, considering the number of assumptions that need to be made, regard-
We have analyzed H, K, and K-band spectra from the inner 3.5×3.5 kpc² of the radio galaxy Cygnus A, obtained with the Gemini NIFS at a spatial resolution of ≈200 pc and velocity resolution of ≈50 km s⁻¹. We have studied the excitation and kinematic properties of the molecular and ionised emitting gas. The main conclusions of this work are:

- The emission-line flux distributions for the ionised gas ([Si]λ1.4305 μm, Paα, [S]1.9201 μm and [Si]1.9630 μm) clearly show a biconical morphology, with the bicone axis observed along the orientation of the radio jet and half-opening angle of 45°. The [Fe] emission lines show a more round flux distribution than those of lines from other ionised species and the H₂ emission is observed mostly in regions outside the ionisation cone.
- Coronal line emission is observed up to the borders of the NIFS field of view (~1.5 arcsec/1.75 kpc). Higher ionisation gas is seen in the easterly cone than in the westerly cone, as observed in the [Si]/Paα and [Si]/Pa intensity ratio maps.
- Emission-line ratio diagnostic diagrams indicate that the H₂ and [Fe] emission lines are consistent with excitation by the central AGN, with some contribution of shocks in a region extending from the nucleus to southwest.
- From the Paα/Brγ line ratio we derive visual extentsions of up to 20 mag and an average value of 12.5 mag. The average value of the electron density is ~900 cm⁻³ as obtained from the [Fe]1.5330 μm/[Fe]1.6440 μm emission-line ratio. Both density and visual extinction are larger than the values derived using optical lines, consistent with the fact that near-IR observations can penetrate more deeply into the gas emission structure and probe denser and more obscured regions.
- We observe two gas kinematic components produced by (i) a rotating disc with major axis oriented along Ψ₀ = 21° ± 2° and projected velocity amplitude of ~150 km s⁻¹, clearly observed in the H₂ velocity field and (ii) outflows within the bicone, with velocities of up to 600 km s⁻¹ observed in ionised gas. Compact nuclear H₂ outflows are seen in the inner 0.5 arcsec, produced by the interaction of the ionised outflows with the gas in the disc, by a lateral expansion of the dusty torus or by the outer side of the biconical winds seen in ionised gas.
- The geometry of the outflows is consistent with a bicone with axis along the orientation of the radio jet, half-opening angle of 45°, making an angle of 30° relative to the plane of the sky with the northwest being the near side of the bicone. Using this geometry along with the observed kinematic properties, we estimate the filling factor of the outflow to be less than 20 per cent of the energy of the total outflow indicated by the hot H₂ blueshifted gas. In addition, numerical simulations indicate that the kinetic energy corresponds to less than 20 per cent of the energy of the total outflow (Richings & Faucher-Giguère 2018) and thus, the power of the multi-phase outflow in Cygnus A may be even larger than the value derived above.

5 CONCLUSIONS

We have analyzed H, K, and K-band spectra from the inner 3.5×3.5 kpc² of the radio galaxy Cygnus A, obtained with the geometry, filling factor and gas density (e.g. Davies et al. 2020). For instance, if we assume N_e ≈ 4450 cm⁻³ derived from the [Ar iv]λ4711,4740 (Sec. 4.2), we obtain M_out ≈ 160 M_⊙ yr⁻¹. Further, if we assume that the geometry of the outflows is a hollow bicone, as suggested for nearby Seyfert galaxies (e.g. Storchi-Bergmann et al. 2010b; Fischer et al. 2013), we find M_out ≈ 100 M_⊙ yr⁻¹ using inner and outer half-opening angles of 40° and 50°, respectively. Using the density estimated from the [S ii] lines in Sec. 4.2, the resulting outflow rate would be about one order of magnitude smaller, but as pointed out in Davies et al. (2020), the electron density derived from the [S ii] lines are significantly smaller than the real density of the outflows. Thus, the mass outflow-rate in ionised gas for Cygnus A may be in the range ~ 100 – 280 M_⊙ yr⁻¹. The AGN in Cygnus A has a bolometric luminosity of (0.5 – 2.0)×10⁴⁶ erg s⁻¹ (Tadhunter et al. 2003) and the derived M_out values above is similar to the ionised outflow rates observed for AGN with similar luminosities (e.g. Davies et al. 2020; Kakkad et al. 2020; Vayner et al. 2021; Dall’Agnol de Oliveira et al. 2020). For instance, if we assume the geometry, filling factor and gas density (e.g. Davies et al. 2020, 2021; Dall’Agnol de Oliveira et al. 2021) we find M_out ≈ 46 M_⊙ yr⁻¹.

We can use the above range of mass outflow rate to estimate the kinetic power of the outflow by

$$\dot{E} \approx \frac{M_{\text{out}}}{2} \left( v_{\text{out}}^2 + 3 \sigma_{\text{out}}^2 \right),$$

where v_{out} is the velocity dispersion of the outflow. Using σ ≈ 700 km s⁻¹ (from Fig. 5) we obtain $\dot{E} \approx (6 – 16) \times 10^{43}$ erg s⁻¹, which corresponds to 0.3 – 3.3 per cent of the AGN bolometric luminosity. If the kinetic power of the outflow is above 0.5 per cent of the AGN luminosity it becomes effective in suppressing the star formation in the host galaxy (Hopkins & Elvis 2010). Thus, the ionised outflows in Cygnus A seem to be powerful enough to affect the evolution of the galaxy. Molecular gas phases of the outflow may also be present, as indicated by the hot H₂ blueshifted gas. In addition, numerical simulations indicate that the kinetic energy corresponds to less than 20 per cent of the energy of the total outflow (Richings & Faucher-Giguère 2018) and thus, the power of the multi-phase outflow in Cygnus A may be even larger than the value derived above.
matities, we obtain ionised mass outflow rates in the range \(\sim 100 - 280 M_\odot \, \text{yr}^{-1}\).

- The kinetic power of the outflows corresponds to 0.3–3.3 per cent of the bolometric luminosity of the AGN in Cygnus A, being powerful enough to suppress star formation in the host galaxy.

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DATA AVAILABILITY

The data used in this paper is available in the Gemini Science Archive at https://archive.gemini.edu/searchform under the project code GN-2006A-C-11. Processed datacubes used will be shared on reasonable request to the corresponding author.

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