Detailed Accretion History of the Supermassive Black Hole in NGC 5972 over the Past $\gtrsim 10^4$ yr through the Extended Emission-line Region

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Abstract

We present integral field spectroscopic observations of NGC 5972 obtained with the Multi-Unit Spectroscopic Explorer at the Very Large Telescope. NGC 5972 is a nearby galaxy containing both an active galactic nucleus (AGN) and an extended emission-line region (EELR) reaching out to $\sim 17$ kpc from the nucleus. We analyze the physical conditions of the EELR using spatially resolved spectra, focusing on the radial dependence of ionization state together with the light-travel time distance to probe the variability of the AGN on $\gtrsim 10^4$ yr timescales. The kinematic analysis suggests multiple components: (a) a faint component following the rotation of the large-scale disk, (b) a component associated with the EELR suggestive of extraplanar gas connected to tidal tails, and (c) a kinematically decoupled nuclear disk. Both the kinematics and the observed tidal tails suggest a major past interaction event. Emission-line diagnostics along the EELR arms typically evidence Seyfert-like emission, implying that the EELR was primarily ionized by the AGN. We generate a set of photoionization models and fit these to different regions along the EELR. This allows us to estimate the bolometric luminosity required at different radii to excite the gas to the observed state. Our results suggest that NGC 5972 is a fading quasar, showing a steady gradual decrease in intrinsic AGN luminosity, and hence the accretion rate onto the SMBH, by a factor $\sim 100$ over the past $5 \times 10^4$ yr.

Unified Astronomy Thesaurus concepts: AGN host galaxies (2017); Active galactic nuclei (16)

1. Introduction

Active galactic nuclei (AGN) can have a significant impact on the interstellar medium of their host galaxies, through the mechanical input of radio jets, wind-driven AGN, and photoionization of the gas (e.g., Morganti 2017). The energy injected into the host galaxy is thought to play a critical regulatory role in both galaxy and supermassive black hole (SMBH) evolution (e.g., Gebhardt et al. 2000; Kormendy & Ho 2013).

The AGN can photoionize gas out to $\gtrsim 1$ kpc, which is considered the so-called narrow-line region (NLR), as the kinematics of this gas are typically $<1000$ km s$^{-1}$. However, observations have shown that AGN-ionized gas can, and often does, extend well beyond this limit. These extended emission-line regions (EELRs) can extend through the entire host galaxy and reach tens of kiloparsecs (e.g., Liu et al. 2013; Harrison et al. 2014). EELRs can exhibit complex morphologies and be spatially and kinematically distinct from the NLR. Some EELRs show no direct morphological relation to the host galaxy and have been connected to tidal tails from galaxy interactions (e.g., Keel et al. 2012) or large-scale outflows (e.g., Harrison et al. 2015), while other EELRs show conical or biconical shapes, with their apex near the active nucleus, and can be considered as large-scale extensions of the NLR. The ionized gas within an EELR can show large velocities, ranging from several hundreds to $>1000$ km s$^{-1}$ with respect to the systemic velocity of the host, while also showing low velocity dispersion (e.g., Fu & Stockton 2009; Husemann et al. 2013).

While early studies connected EELRs with the presence of radio jets (Stockton et al. 2006), they have also been observed in active galaxies with no appreciable radio emission (Husemann et al. 2013). Some EELRs show narrow line widths and modest electron temperatures, indicating that they must be ionized by radiation from the nucleus, rather than direct interaction with either a radio jet or an outflow, for which the line width and electron temperature would be much higher owing to the presence of shocks (e.g., Knese et al. 2020). EELRs can potentially offer a unique way to probe the effect of the AGN on the galaxy due to their physical extension, which connects the large scales of the host with the active nucleus (e.g., Harrison et al. 2015; Sun et al. 2017). Furthermore, by considering the light-travel time to the clouds and then to us, we can obtain a view into the past of the AGN, on longer timescales than typical AGN variability (e.g., Lintott et al. 2009; Dadina et al. 2010; Keel et al. 2012).

The suggestion that EELRs can be light echoes from a former high-luminosity AGN was originally explored in a...
nearby, highly ionized, extended cloud near the active galaxy IC 2497 (Lintott et al. 2009; Sartori et al. 2016); this object and others alike have been since called Voorwerpjes. The current AGN luminosity failed to account for the ionization observed in the cloud, thus suggesting that the AGN decreased by a factor $\sim$100 in luminosity over a $\sim$10$^5$ yr timescale (Lintott et al. 2009; Schawinski et al. 2010; Keel et al. 2012). Further studies of nearby Voorwerpjes have found comparable variability amplitudes in similar timescales (Keel et al. 2012, 2017; Sartori et al. 2018).

AGN variability has been observed and inferred to occur on virtually all timescales, ranging from seconds, to days, to decades, to $>10^4$ yr. These different timescales indicate that there are likely different physical processes at play at different spatial scales of the system, from the SMBH vicinity to galaxy-wide scale. Days to years variability, observed in the optical and UV and probed by ensemble analysis, may arise from accretion disk instabilities (e.g., Sesar et al. 2006; Caplar et al. 2017; Dexter & Begelman 2019), while possible explanations for years-to-decades timescales, observed in the so-called “changing-look AGN,” include changes in accretion rate or accretion disk structure (e.g., LaMassa et al. 2015; MacLeod et al. 2019; Graham et al. 2020). Variability on longer timescales ($>10^4$ yr), probed through AGN-photoionized EELRs (e.g., Lintott et al. 2009; Schawinski et al. 2010; Keel et al. 2012), is possibly linked to dramatic changes in accretion rate. Simulations indicate mergers, bar-induced instabilities, and clumpy accretion as possible mechanisms behind these changes (e.g., Hopkins & Quataert 2010; Bournaud et al. 2011).

A typical AGN duty cycle is estimated to last $10^7$–$10^9$ yr (Marconi et al. 2004). This, however, does not constrain whether the total mass growth is achieved during a single active accretion phase or is broken up in shorter phases. Simulations and theoretical models have addressed accretion variability (e.g., Gabor & Bournaud 2013; King & Nixon 2015; Schawinski et al. 2015; Sartori et al. 2018, 2019), suggesting a typical timescale for AGN phases of $10^7$ yr, implying that nearby AGN switch “on” rapidly during $\sim10^3$ yr and stay on for $\sim10^5$ yr before switching “off.” The AGN continues “flickering” on these $10^3$ yr cycles, resulting in a total $10^7$–$10^9$ yr “on” lifetime over the course of the host.

Quantifying the effect the AGN has on the host galaxy evolution requires a better understanding of how the nuclear activity evolves and varies during the galaxy lifetime. Following the analysis of IC 2497, efforts to find similar objects in the nearby universe were made, based on Sloan Digital Sky Survey DR5 optical imaging. In order to accomplish this, both targeted and serendipitous searches were carried out at $z<0.1$ by Galaxy Zoo volunteers during a 6-week period (Keel et al. 2012). This search retrieved 19 objects, including NGC 5972, a nearby ($z = 0.02974$, where 1$^\circ$ corresponds to 0.593 kpc) Seyfert 2 galaxy (Véron-Cetty & Véron 2006).

NGC 5972 was previously known for the presence of powerful ($10^{23.9}$ WHz$^{-1}$ at 4850 MHz) extended (9/4, corresponding to 0.3 Mpc) double radio lobes (Condon & Broderick 1988; Veron & Veron-Cetty 1995) that extend along a position angle (PA) of 100$^\circ$, almost perpendicular to the major axis of the optical emission.

The galaxy has been morphologically classified as an S0/a. Further modeling of the $I$-band luminosity profile shows complex residuals that indicate a possible merger or galaxy interaction event (Veron & Veron-Cetty 1995). The EELRs extend to a radius of 20$^\circ$ from the center, which corresponds to $\sim$12 kpc, forming a double-helix shape that shows a highly ionized complex filamentary structure (narrow- and medium-band HST imaging; Keel et al. 2015).

In this paper we present results from Very Large Telescope (VLT)/MUSE observations of NGC 5972. We study the long-term variability of the source by analyzing the changes in luminosity required to ionize the EELR to its current state as a function of radius.

This paper is organized as follows. In Section 2 we describe the observations and the data reduction process. In Section 3 we present the results of our analysis. The results are discussed and summarized in Sections 4 and 5, respectively.

2. Observations and Data Reduction

The Multi-Unit Spectroscopic Explorer (MUSE; Bacon et al. 2010) is an integral field spectrograph installed on the VLT. Its field of view (FOV) in wide field mode (WFM) covers $1' \times 1'$, with a pixel scale of 0.2'. The wavelength range spans $\sim$4600–9300 Å, and the resolving power is $R = 1770–3590$.

NGC 5972 was observed with MUSE in WFM on the night of 2019 March 10 (program ID 0102.B-0107; PI L. Sartori), in two observing blocks (OBs). Each OB consisted of three on-target observations with an exposure of 950 s each, 1/4 dithers, and a seeing constraint of 1$''$. The last exposure of the second OB was finished 8 minutes into twilight, causing a small increase in the blue background. The exposure was included in the analysis. The data were reduced with the ESO VLT/MUSE pipeline (v2.8) under the ESO Reflex environment (Freudling et al. 2013). Briefly, this pipeline generates a master bias and flat. This is followed by the wavelength calibration, employing the arc-lamp exposures, and afterward the flux calibration. Both of these are applied to the raw science exposures.

A sky model is created from selected pixels free of source emission and is subtracted from the science exposures. The coordinate offsets are calculated for each FOV image to align the six exposures. Finally, we combined all the exposures by resampling the overlapping pixels to obtain the final data cube.

The final data cube has a mean seeing-limited spatial resolution of $\sim0.7'$, as estimated from a point source located in the southern portion of the FOV. The data cube is rotated 35$^\circ$ so north is up and east to the left. This results in our final data cube containing 432 $\times$ 431 spaxels, corresponding to 86$''$4 and 86$''$2. At the redshift of NGC 5972, the physical area observed is $50 \times 50$ kpc$^2$, sufficient to cover the entire galaxy and its EELR, as can be seen in Figure 1.

3. Results

In this section we present the results from our analysis of the MUSE observations of NGC 5972. The results are organized as follows. We first present the fitting to the stellar component (Section 3.1). In Section 3.2 we present an analysis of the ionized gas component by studying the moment maps from the emission lines, the dust extinction, and the dominant ionization mechanism. In Section 3.3 we present a kinematic analysis of the stellar and ionized gas components. Finally, in Section 3.4 we present our analysis of the EELR, comparing the observed emission-line ratios to ionization models in order to constrain the required luminosity to ionize the gas to its observed state.
we create a color-composite image (Figure 1) by collapsing three separate sections of the data cube, one that encompasses the [O III] emission line, the second one for the Hα emission line, and a third one collapsing the range 7000–9000 Å to represent the stellar continuum. These three images are represented by green, red, and white pseudocolors, respectively. Each color image was stretched with a logarithmic scale before being combined. This composite image shows the largescale morphology of the ionized gas, as well as the filamentary complex structure that extends from the center to the N and S. The emission-line gas forms a double-helix shape to the S, and an arm that seems to twist on itself toward the W is observed in the N. Low-luminosity tidal tails are observed beyond these bright arms both to the NE and to the SE.

Narrowband imaging obtained with the 2.1 m telescope at Kitt Peak in Arizona, where V-band continuum has been subtracted from the narrow filter centered at redshifted [O III], shows ionized structure reaching 70″ as a lower limit in the S and up to 81″ in the N; this corresponds to 41 and 48 kpc, respectively (W. Keel, private communication). When considering fainter features that are revealed with smoothing, these limits can extend up to 76″ and 91″ for the S and N regions, respectively.

3.1. Stellar Component Fitting

To analyze the stellar component of NGC 5972, we use the Python implementation of the penalized pXel-Fitting software (pPXF; Cappellari & Emsellem 2004; Cappellari 2017), together with the MILES single stellar population (SSP) models (Vazdekis et al. 2015) as spectral templates for the stellar continuum. The templates have an intrinsic spectral resolution of 2.51 Å and were broadened to the wavelength-dependent MUSE resolution before any fits with pPXF were performed. We further adopt the line-spread function (LSF) model of the MUSE spectra as described in Bacon et al. (2017).

The first step in the analysis is to apply the adaptive Voronoi tessellation routine of Cappellari & Copin (2003), to guarantee a minimum signal-to-noise ratio (S/N) across the entire FOV, in order to ensure reliability of the measurement for the stellar component. The S/N is measured using the der_SNR algorithm (Stoehr et al. 2008) in the wavelength range 6400 ≤ λ (Å) ≤ 6500, as there are no strong emission lines present in this spectral window. With this we achieve a minimum S/N of 50, on average per spectral bin, in 1407 spatial bins, in contrast to the 180,000 original pixels. Furthermore, we masked the FOV to exclude spaxels with S/N < 4.

The first run of pPXF was unregularized, fitting the wavelength range 4800–7000 Å. We masked the following emission lines present in this range, with a width of 1800 km s^{-1}: Hβ λ4861, [O III] λ4958, [O III] λ5007, [N I] λ5197, [N I] λ5200, He I λ5875, [O I] λ6300, [O I] λ6363, [N II] λ6547, Hα λ6562, [N II] λ6583, [S II] λ6716, and [S II] λ6730. We use a fourth-order multiplicative Legendre polynomial to match the overall spectral shape of the data. The purpose of this first fit is to derive the stellar component kinematics. In Figure 2 we show an example of the pPXF fitting to one of the central Voronoi bins.

A fit of elliptical isophotes (Figure 3) to the stellar moment 0 map, as obtained from the pPXF fit, shows that the inner region ≤ 2″, Figure 4) is best fitted with a different PA (≈15°) and ellipticity (e ≈ 0.1) than the rest of the disk (PA ≈ 3°, e ≈ 0.25).

In Figure 5 we show the integrated flux distribution (moment 0) obtained from collapsing the cube near 9000 Å with a 200 Å range. On Figure 6 we show the stellar component velocity field (moment 1) and velocity dispersion (moment 2) maps from the pPXF fit. The velocity distribution shows a fairly regularly rotating system that reaches velocities of ±150 km s^{-1} along a PA ≈ 10°. However, a slightly bent zero-velocity contour and some blueshifted (redshifted) features in the southern (northern) regions indicate the presence of a perturbation to the rotation. While the velocity dispersion map shows a distribution peaking in the center, as expected for a rotating disk, the values of up to ~220 km s^{-1} (slightly higher than the rotation velocities) suggest some turbulence present in the system.

The second pPXF run is regularized to impose a smoothness constraint on the solution, applying the “REGUL” option on pPXF. For this fit we mask the emission lines and apply an eight-order multiplicative Legendre polynomial, fixing the stellar kinematics to those of the first run to avoid degeneracies between stellar velocity dispersion and metallicity. Weights are applied to every template, which are regularly sampled on an age and metallicity grid that covers 0.03 < Age (Gyr) < 14 and −2.27 < Metallicity (dex) < 0.40. The regularization allows templates with similar age and metallicity to have smoothly varying weights. The stellar age map is shown in Figure 7, where we can observe a stellar population distribution with older populations at the center and younger populations at larger radii.

3.2. Emission Lines

3.2.1. Moment Maps

We run one further pPXF fit to the complete unbinned FOV with the purpose of subtracting the stellar continuum from the data cube. We use the unbinned data cube in order to recover the fine spatial structure of the gas component. This is possible owing to the high S/N of the emission lines in contrast to the absorption lines. Following the same procedure
as above, we masked the emission lines. A scaled version of the best-fitted stellar continuum is subtracted to every spaxel of the unbinned cube associated with a given bin. We therefore obtain a continuum-free data cube, from which we can recover the emission lines. The total fluxes of the emission lines are model-dependent estimates based on this pPXF fitting.

The emission lines, in every bin, were then fitted with Gaussian profiles, tying the [O III] $\lambda\lambda$4958, 5007 and [N II] $\lambda\lambda$6548, 6562 flux ratios, H$\beta$ and H$\alpha$ line widths, relative positions of the emission lines, and width of the forbidden emission lines to the [O III] $\lambda$5007 line width, given its considerably higher S/N. This approach does not leave considerable residuals in the other emission lines. This fit was made for all spaxels with S/N > 4, where the S/N was calculated in a wavelength range that includes the [O III] $\lambda$5007 forbidden emission line. From this one Gaussian component fit we extract the flux and kinematics for the emission lines as shown in Figure 8. The flux distribution of the gas component shows a complex spatial distribution. The ionized gas extends farther out than the stellar component, forming a “helix”-shaped pattern that displays very fine filamentary structure. High-S/N ionized gas extends $\sim$25″ from the center, while fainter structure is observed beyond this radius, up to 32″.

The northern trail of gas appears to extend from the center and then curve back toward the nucleus, forming at the same time as fine gas filaments toward the NE. In the southern region the ionized gas appears to extend from the nucleus in two arms. One curves slightly toward the E and shows higher flux. The other extends from the E of the nucleus and curves toward the W. The gas velocity field shows complex kinematics that, while mainly redshifted in the N region and blueshifted in the S, do not appear to be a primarily rotating disk, in contrast to the stellar component. This is supported by the distribution of the velocity dispersion map, which shows a complex distribution that does not resemble the expectation for a purely rotating disk.

### 3.2.2. Dust Extinction

To obtain a map of the extinction by dust in the line of sight, we calculate the Balmer decrement (using the H$\alpha$/H$\beta$ emission-line ratio). From this, we estimate the total extinction (A$_V$), in the V band, following Domínguez et al. (2013). We use the average Galactic extinction curve from Osterbrock & Ferland (2006) assuming an intrinsic value of H$\alpha$/H$\beta$ = 2.86, which corresponds to a temperature $T$ = 10$^4$ K and electron density $n_e$ = 10° cm$^{-3}$ for case B recombination. The extinction map (Figure 9) shows the presence of dust in an upside-down V shape, with its apex close to the center, and some dust extending along the SE and SW arms. It has been suggested (Keel et al. 2015) that these dust lanes were formed by a differentially precessing warped disk, as modeled by Steiman-Cameron & Durisen (1988). We use the derived extinction values to correct the emission-line fluxes used in the analysis of Section 3.4.

A starlight attenuation map was already created for this galaxy based on HST WFC3 imaging, as presented in Figure 7 of Keel et al. (2015). Assuming that it represents pure continuum divided by a smooth model. This map shows almost no starlight attenuation in the SE arm, which suggests that it is on the far side of the system and only absorbs a small fraction of the starlight behind it. The three dots observed in Figure 9 in the NW arm match well with the features observed in the starlight attenuation map, implying that the filament in that region is in front of most of the starlight. Finally, a dust feature is observed aligned N to S from 3′5 to 5′6; this feature is S of the nucleus and does not show a counterpart in the Balmer decrement map, indicating that it may be decoupled from the ionized structure.

### 3.2.3. Origin of the Ionized Gas

We compute emission-line ratios from the fluxes obtained from the one-component Gaussian fit, in order to analyze the distribution and origin of the ionized gas. We use the [O III]/H$\beta$ and [N II]/H$\alpha$ emission-line ratios to create a Baldwin, Phillips, & Terlevich (BPT; Baldwin et al. 1981) diagram,
where every spaxel is classified as star-forming, composite, LINER, or Seyfert. This color-coded classification is presented in Figures 10–11 and shows the presence of Seyfert-like ionization along the arms that form the helix pattern, which is surrounded by a mixture of LINER-like and Composite ionization. The [O III]/Hβ map (Figure 12) shows that [O III] dominates over Hβ in the arms, with higher [O III]-to-Hβ ratio inside the arms, falling to a lower ratio quickly outside the filamentary structure. The [N II]/Hα map shows the structure inside the arms, where Hα emission is higher than the [N II]. Some nodes with higher Hα emission are observed near the nucleus and in the filamentary structure of the arms.

The resolved BPT reveals that AGN-ionized gas extends uninterrupted from the central region up to radius ∼22″ and that AGN photoionization is the main ionization mechanism observed in the galactic disk, with Seyfert-like ionization in the arms and mostly LINER-like ionization in the disk outside the arms. To evaluate the possibility that the ionized region extends over a bicone centered in the nucleus, tracing a large-scale extended NLR, we assume that the observed ionization is bounded by the availability of radiation rather than gas. We estimate a required full opening angle for the ionization cones of ∼75° to encompass the entire EELR. This angle is estimated from the projected angular width of each half of a notional bicone that encompasses the observed ionized regions. Given the projection effects, this angle is an upper limit. Making the ionization cones narrower than the observed ∼75° on each side would require the axis to be closer to our line of sight, putting all the EELR features farther from the AGN. In the context of the analysis conducted in Section 3.4, this would imply an even larger mismatch between the present-day AGN luminosity and that of the ionized clouds.

### 3.3. Kinematics

#### 3.3.1. Stellar Component

We modeled the kinematics of the stellar component using the 2DFIT task included in the package 3DBarolo (Di Teodoro & Fraternali 2015), which fits tilted rings of a chosen thickness; we use a width of 0″4, fixing the center (as the peak of the continuum) and the systemic velocity and varying the rotation velocity, the PA, and the inclination for every ring. The best-fit model and the residuals are shown in Figure 13. The residuals, obtained by subtracting the model of our stellar...
velocity map from the measured one, show a small blueshifted excess S and SE of the nucleus and redshifted E and SW of the nucleus. Some of these features coincide with the region where the arms observed in the gas component are present. The model reaches $\pm 150\text{ km s}^{-1}$, and it has a curved zero-velocity contour, indicative of some perturbation in the disk. Along the different radii, the PA remains close to 6°, varying to $\sim 353°$ at radius $\sim 15''$ and then returning to 6°. The inclination remains closer to 41° in the inner $\sim 15''$ and increases to $\sim 50°$ at larger radii. The rotation curve reaches $\sim 150\text{ km s}^{-1}$ at radius 7'', and remains more or less constant until radius 15'', from where it increases steadily up to 220 km s$^{-1}$.

### 3.3.2. Gas Component

The moment 1 for the [O III] emission line reveals complex kinematics that seem to be, at least partially, rotating on a disk. To model this kinematics, we utilize the 3Dfit routine, to perform a 3D fitting to a data cube trimmed on the wavelength axis to contain only the [O III] emission line. The fit is done in two stages. For the first stage, we leave as free parameters the inclination, major-axis PA, circular velocity, and velocity dispersion. From this fit we obtain values for the inclination and the PA on each radius. The means of these parameters over all the rings are 14° and 35°, respectively. The values from ring to ring do not deviate considerably from the mean values. For the second stage, we fix the center to the peak of the continuum, and the inclination (35°) is fixed to the value obtained in stage 1. We leave the PA as a free parameter, but we use the mean value from stage 1 as the initial guess for the second fit. The radial velocity is fixed at zero at this point, assuming only a rotational component. The code fits a pure circular rotation model to the data cube, while the noncircular motions can be observed in a residual map (Figure 14, and a zoomed-in version in Figure 15), in which very complex structures can be observed. The fitted model shows a large-scale rotation disk that reaches $\sim 120\text{ km s}^{-1}$. In the inner radius (6''), a higher velocity gradient is observed reaching $\sim 200\text{ km s}^{-1}$. This feature can correspond to an inner disk that has been disrupted, given the complex distribution observed in the velocity field. In the nuclear 1'', a feature can be observed along PA = 100°, with velocities of $\sim 50\text{ km s}^{-1}$. To confirm that these features are not model dependent, we create a position–velocity diagram (PVD, Figure 16), which consists of extracting the flux along a slit from the data cube. The positions are taken relative to the center, and the wavelength is transformed into a velocity offset centered at systemic velocity. In the PVD extracted along the minor axis, two loci can also be observed (Figure 3.3.2). Considering the possibility of the near side corresponding to the W side of the disk, as the extinction map indicates, this feature could be explained by a nuclear outflow; we further explore this nuclear outflow by fitting the spectra with two Gaussian components in Appendix A.

A final feature is observed along the NW and SE arms, which show excess redshift on the approaching side of the galaxy and blueshift on the receding side, with velocities reaching $\sim 300\text{ km s}^{-1}$ (Figure 17). If we consider that the near side corresponds to the W side of the disk, this feature would correspond to an inflow in the plane of the galaxy disk. However, given the high velocities reached for an inflow, it is possible that, given the uncertainty about the 3D distribution of the gas, it corresponds to a secondary component in the line of sight, caused by extraplanar gas related to tidal debris.

To further understand the kinematics of the gas in NGC 5972, we extract the spectra from 6'' apertures in different regions of the disk, along the arms (Figures 18 and 19). The spectral windows, centered on the [O III] emission line, show that the ionized gas along the arms is more redshifted (blueshifted) on the receding (approaching) side than the stellar rotation, while in apertures outside the arms, the gas seems to coincide with the stellar rotation (apertures 23–24 and 4–6). This can also be observed by comparing with the PVDs extracted from slits along the major and minor axis (Figure 3.3.2) and along PA $\sim 150°$, which crosses the SE and
NW arms (Figure 17). The arms seem to be dominated by a component that has velocities deviating from the model by about 150 km s\(^{-1}\) on both the redshifted and blueshifted sides. The spectra of these NW and SE arms (apertures 8–10 and 14–17) show that a secondary component, appearing as an asymmetric wing (or tail) in the line profiles, follows the rotation, indicating that the emission in these apertures is dominated by a secondary kinematic component, which may be emission from extraplanar gas in the line of sight.

3.4. Extended Emission-line Region

Having established that the gas from the arms has been ionized primarily by the AGN (See Section 3.2.3), and given the extension of the ionized clouds, which is large enough to be substantially influenced by light-travel time effects, we can trace the AGN luminosity from the nucleus to \(\sim 17\) kpc and assess possible luminosity changes over time. For this analysis we compare our observed emission-line ratios to the spectra obtained from photoionization models to derive a best-fit ionization parameter (defined as the dimensionless ratio of hydrogen-ionizing photons to total-hydrogen densities) and use it to estimate the AGN luminosity required to produce the EELR ionization. In Figure 20 we present the apertures (radius 0″6) where the analysis was carried out, example of this in different apertures can be found in Figure 21. We separated the regions in the arms “A” (N arm), “B” (SE arm), and “C” (SW arm), each covering distances of 11, 12, and 8 kpc to the inner kiloparsec, respectively. Furthermore, we add apertures over the northern tidal tail of the “A” arm, labeled as “AT,” which covers between 11 and 17 kpc. Given the low flux in this region, we use apertures of 1″/2. The farthest distance corresponds to \(5.5 \times 10^4\) lt-yr, located in the A arm. For every

![Figure 8. Moment maps from a one-component Gaussian fit to the emission lines H\(_\alpha\) (top panels) and [O III] (bottom panels). Left panels: moment 0 maps (flux distribution). Color bar in \(10^{-17}\) erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\). Middle panels: moment 1 maps (velocity distribution). Color bar in km s\(^{-1}\). Right panels: moment 2 maps (velocity dispersion). Color bar in km s\(^{-1}\). All the maps are clipped at 3\(\sigma\).](image-url)
aperture we obtain the integrated spectrum, which is fitted with Gaussian profiles to obtain the fluxes for the emission lines Hβ, [O III] λ5007, [O II] λ6300, [N II] λλ6547, 6583, Hα λ6563, and [S II] λλ6716, 6731.

After creating a continuous sequence of apertures from the center covering the extension of every arm, we fill the vicinity of each aperture with 30 new apertures of the same size. From these new apertures we choose the one with the largest S/N; to
the corresponding spectra we fitted a two-component Gaussian profile to separate the multiple kinematic components. An example of this can be observed in Figure 22.

To model the emission-line ratios observed in our data, we use the photoionization code CLOUDY (version 17.02 last described in Ferland et al. 2017), following the method outlined in Treister et al. (2018). CLOUDY resolves the equations of thermal and statistical equilibrium on a planeparallel slab of gas being illuminated and ionized by a central source. For the central source we consider a spectrum consistent with the observed spectra of local AGN (e.g., Elvis et al. 1994). This spectrum is described by a broken power law ($L_\nu \propto \nu^{\alpha}$), where $\alpha = -0.5$ for $E < 13.6$ eV, $\alpha = -1.5$ for $13.6$ eV $< E < 0.5$ keV, and $\alpha = -0.8$ for $E > 0.5$ keV.

The ionization parameter is defined as the dimensionless ratio of number of ionizing photons to hydrogen atoms at the face of the gas cloud:

$$U = \frac{Q(H)}{4\pi r_0^2 n(H)c},$$

where $L_\nu$ is the AGN luminosity as a function of frequency, $h$ is the Planck constant, and $r_0 = 13.6$ eV $h^{-1}$ is the frequency corresponding to the ionization potential of hydrogen (Osterbrock & Ferland 2006).

The first run of simulations assumes solar metallicity with a grid covering the ionization parameter ($-3.5 < U < -2.0$) and the hydrogen density ($1.0 < n_H < 5.0$). However, these simulations do not cover the entire range of measurements on a BPT diagram. Thus, following Bennert et al. (2006), we run a series of models changing the metallicity from 1.0 to 4.0 times the solar metallicity, and a third calculation changing only the nitrogen and sulfur metallicity to 1.5 $Z_\odot$ and $1.5 \times Z_\odot$, respectively, while maintaining the other elements at their solar values, best covers the parameter space of our data (see Figure 23) for arms “A,” “B,” and “C.” This metallicity, however, does not fit well the fluxes observed for arm “AT.” Therefore, we maintain a solar metallicity. More details on the metallicity choice can be found in Appendix B.

To obtain a model that fits the observations, it should be able to reproduce all the observed emission-line ratios relative to H/β. For each aperture we compare the observed line ratios of [O III], [N II], [S II], Hα, and [O I] scaled to H/β to those obtained from the simulations and choose the combination of ionization parameter and hydrogen density that delivers the best fit. We consider an acceptable fit when the difference between the emission-line ratios is less than a factor of two for
every line ratio. For $\lambda 5007$ we require the model to match the observations within 50%. From the models that meet these criteria, we choose the one with the smallest reduced $\chi^2$.

Following previous EELR analysis (Keel et al. 2012), we assume a fully ionized gas, and thus we can estimate the atomic hydrogen column density as being the same as the electron density ($n_H = n_e$). The electron density can be constrained from the $\text{[S II]}\lambda 6716/\lambda 6730$ emission-line ratio (hereafter referred to as the $\text{[S II]}$ ratio). We use the Python package $\text{PyNeb}$ which computes emission-line emissivities (Luridiana et al. 2012), to obtain the $n_e$ from the observed $\text{[S II]}$ ratio, assuming a 10$^4$ K temperature (Osterbrock & Ferland 2006). The $\chi^2$ maps for the $U$ and $n_H$ parameters (Figure 21) show that for a given $U$ the $n_H$ remains roughly constant. Considering that the required bolometric luminosity of the AGN is proportional to $U \times n_H$, and since the $n_H$ is not well constrained by the CLOUDY fit, we adopt the electron density from the $\text{[S II]}$ ratio as $n_H$. However, for completeness, and given that for every aperture do the $n_H$ value for the CLOUDY fit and the $\text{[S II]}$ line ratio fall in the same $U$ value, we calculate two different bolometric luminosities: one assuming the density from the $\text{[S II]}$ ratio (hereafter referred to as "model 1"), and one assuming the hydrogen density from the best-fit CLOUDY model (hereafter "model 2").

Using the obtained ionization parameter and hydrogen density values, and assuming that the distance to the cloud is traced by the projected distance from the central source to the aperture, we can estimate $Q(H)$ for each aperture. Then, integrating our SED, we can use the obtained $Q(H)$ to further estimate the bolometric luminosity required to ionize the gas at each point.

Figure 15. Same as the right panel of Figure 14, but zoomed in at the central region.

Figure 16. PVD extracted from the continuum-subtracted data cube along the major (top panel) and minor (bottom panel) axes, centered on the $\text{[O III]}$ emission line. Red contours show the PVD from the best-fitted 3D model obtained with the 3DBarolo routine.

Figure 17. PVD extracted along PA = 150°; this angle crosses along the NW and SE arms. The red dots mark the best-fit model for the stellar component, and the blue dots mark the best-fit model for the ionized gas component as fitted to a data cube centered in the $\text{[O III]}$ emission line.

Figure 18. Moment 1 map for the $\text{[O III]}$ emission line; overlaid in black are the apertures used to extract the spectra. Gray contours show the moment 0 distribution for the $\text{[O III]}$ emission line.
In Figure 24 we show the bolometric luminosity as a function of distance to the nucleus, using the electron density from model 1 (blue shaded area) and the electron density from model 2 (red shaded area).

The errors are derived from Monte Carlo (MC) simulations, where random noise is added to the observed emission-line ratios. These simulations are then fitted with the described technique, and the errors are considered as the standard deviation (stdv). For model 2, we consider the stdv for the U and \(n_H\) parameters. For model 1, the noise is applied first to the \([\text{S II}]\) ratio, and we obtain the error as the stdv in electron density. With this value, we fix the density and fit the ionization parameter in the same manner as before. The results on both models show a clear trend of increasing luminosity with distance from the center. Both \(L_{\text{bol}}\) derived from the different density calculations follow the same trend and overlap at some radii. For model 1 we see a change in luminosity of \(\sim 124\) times between 1 and 17 kpc, which, considering time travel distance, corresponds to \(5 \times 10^7\) yr. For model 2 the luminosity change is \(\sim 160\) times.

The maximum bolometric luminosity is observed in the “AT” arm and reaches \(4 \times 10^{46}\) erg \(s^{-1}\) at \(\sim 17\) kpc from the center for model 1 and \(10^{47}\) erg \(s^{-1}\) for model 2.

The AGN in NGC 5972 has been reported to have an \(L(15–55\text{ keV}) = 1.0 \times 10^{43}\) erg \(s^{-1}\) (Marchesi et al. 2017) and an \(L(\text{FIR}) < 5.5 \times 10^{43}\) (Keel et al. 2012), corresponding to an ionizing luminosity of \(L_{\text{ion}} > 7.8 \times 10^{43}\) erg \(s^{-1}\). We estimate the present-day bolometric luminosity from the \([\text{O III}]\) emission line in the apertures closest to the center to be \(\sim 2 \times 10^{44}\) erg \(s^{-1}\), applying the correction factor of Heckman et al. (2004). Our results are in concordance with the values reported in Keel et al. (2012) for this object, who estimate an \(L_{\text{ion}} < 9.8 \times 10^{46}\) erg \(s^{-1}\) at 15–18 kpc, in contrast with present-day \(L_{\text{ion}} > 7.8 \times 10^{43}\) erg \(s^{-1}\) for the AGN in its current accretion state.

4. Discussion

4.1. Morphology and Kinematics

The spatial resolution provided by the MUSE observations allows us to spatially resolve and characterize the EELR. The most striking features of this EELR are the arms seen to the N and S of the center. Additionally, faint streams of gas reminiscent of tidal tails are observed toward the NE and SE. The spectra of these arms show that they are dominated by AGN-photoionized gas. The kinematic analysis shows complex structure with a component that follows a usual galaxy disk rotation reaching \(120\) km \(s^{-1}\). Additionally, the NW and SE arms are a clearly distinct independent component. While the kinematics of the arms follow the sense of rotation in the disk, with blueshifted (redshifted) emission on the SE (NW), they show larger offsets from a simple rotation model. Given the inclination of the disk, this feature could represent an outflow if the blueshifted emission is on the near side of the galaxy. The velocities reached by this feature (\(\sim 300\) km \(s^{-1}\)) are consistent with an outflow in a low or moderate power source. However, another possibility is that this feature is another component in the line of sight, due to extraplanar gas. Finally, we identify a
Figure 20. Moment 0 map for the [S II] emission line; overplotted are the apertures on each arm, in red for arm “A,” yellow for “AT,” green for “B,” and blue for “C.” The color bar is in $10^{-20}$ erg s$^{-1}$ cm$^{-2}$Å$^{-1}$ units, with an asinh scale to highlight the faint tidal tails.

kinematically decoupled inner disk (radius 6″, peak velocity $\sim 200$ km s$^{-1}$). Inside the disk, in the inner 1″ we observe a 50 km s$^{-1}$ feature along PA = 100° that could be an inflow if the NE side of the galaxy is the near side. Given the presence of tidal features and the inner disk, which seems kinematically decoupled from the large-scale disk, it is possible that this galaxy has experienced a merger or close-encounter event in the past. This event could have tidally disrupted the arms into the galaxy plane. Considering this inclination, the difference in luminosity over the past 100 yr. Using the photoionization code CLOUDY, we have created models that cover a range of ionization parameter, metallicity, and hydrogen density, which we matched to the observed spectra from different apertures along the arms of ionized gas. To obtain a bolometric luminosity based on these models, some caveats must be taken into consideration:

(a) **Geometry:** we have assumed that the distance from the center to each ionized gas cloud corresponds to the projected distance in the plane of the sky between the two points ($r_{\text{proj}}$). However, it is possible that the ionized gas is not in the plane of the galaxy disk. In this case the true distance will correspond to $r_{\text{proj}}/\sin(i)$, where $i$ is the inclination of the cloud with respect to the galaxy plane. Considering this inclination, the difference in epochs between the currently observed $L_{\text{bol}}$ and that inferred from the cloud emission corresponds to

$$\Delta t = \frac{r_{\text{proj}}}{c \sin(i)} (1 - \cos(i)).$$

(b) **Density:** In the case of model 1, where the gas density was derived from the [S II] emission-line ratio, it is important to consider that for electron density values between $\sim 100$ and 1000 cm$^{-3}$ the slope in the conversion curve is steep (Osterbrock & Ferland 2006), and thus small changes in the [S II] ratios can translate into largely different electron density values.

(c) **Metallicity:** In this analysis we assume solar abundances for arms “A,” “B,” and “C,” which are sufficient to model the physical conditions of NLRs (as suggested by Kraemer & Crenshaw 2000). However, the line ratios observed on the “AT” arm do not fit within our grid of simulations while assuming solar metallicity. Thus, we vary the metallicity until it matches the observed values.

Taking this into consideration, we obtain a bolometric luminosity change versus light-travel time along the cloud, based on the best-fitted CLOUDY model. To test the consistency with previous analysis in Figure 25, we show a comparison of the required rate of ionizing photons ($Q$) from our CLOUDY models versus the values obtained by Keel et al. (2017) from recombination balance, which represents a lower limit. There is good agreement between both methods.
For model 1, the apertures located in the bright arms (“A”–“C”) show a decrease of \( \sim 40 \) times in bolometric luminosity between 10 and 1.2 kpc. However, the fainter tidal tail that covers between 11 and 17 kpc shows that this increase can reach a 125 times difference, reaching bolometric luminosities of \( \sim 5 \times 10^{46} \) erg s\(^{-1} \) at \( \sim 17 \) kpc. This external region was not covered previously in Keel et al. (2017). We compare the largest bolometric luminosities obtained from our analysis with the AGN luminosity as derived from the WISE mid-IR and far-IR luminosity. This corresponds to a current AGN bolometric luminosity of \( 2 \times 10^{44} \) erg s\(^{-1} \) (Keel et al. 2017). This implies a decrease of 85 times when considering only the “A”–“C” arms, over the past \( \sim 3 \times 10^{4} \) yr, or \( \sim 250 \) times when considering the fainter “AT” arm, over the past \( 5 \times 10^{6} \) yr. For model 2, we see a difference of 80 between 1.2 and 10 kpc and 160 between 1.2 and 17 kpc. The difference between the largest bolometric luminosity with the current bolometric luminosity for this model is 790.

Support for order-of-magnitude variations in the AGN accretion state on \( 10^{5}–10^{6} \) yr timescales includes simulations (Novak et al. 2011; Gabor & Bournaud 2013; Yuan et al. 2018), observational arguments (e.g., Schawinski et al. 2015; Sartori et al. 2018), and theoretical models (Martini & Schneider 2003; King & Nixon 2015). It is possible that the observed short-timescale variability is caused by rapid AGN duty cycles (“flickering”; Schawinski et al. 2015). Possible scenarios that could explain the short timescales for these cycles include the following:

(a) Simulations of feedback-regulated BH accretion, which suggest changes in the character of the accretion over time, from well-separated sharp bursts to chaotic, stochastic accretion. These bursts are needed to prevent gas pileup and can be caused by interactions between radiation pressure and winds.
Figure 24. Bolometric luminosity vs. projected distance from the center. The different symbols represent apertures over different arms. The shaded areas represent the error for each measurement from MC simulations to the data. The blue shaded area corresponds to the data obtained from model 1. Model 1 corresponds to the bolometric luminosity obtained assuming that the gas density is equivalent to the electron density derived from the [S II] line ratio, fixing this parameter in the fitting to the photoionization simulations, using the code CLOUDY. In model 2 we leave as free parameters the ionization parameter and the gas density in the photoionization simulations, which results in different $L_{\text{bol}}$ values for both approaches. There is a clear tendency of increasing $L_{\text{bol}}$ with projected distance from the center for both models. This implies a change of $\sim 120$ (for model 1) and $\sim 160$ (for model 2) times in luminosity over the past $5 \times 10^4$ yr.

with the galactic gas. The bursts of activity are followed by a rapid shutdown on timescales of $\sim 10^5$ (Ciotti et al. 2010; Novak et al. 2011).

(b) Chaotic cold accretion, whereby the AGN flickering can be caused by cold infalling gas that tends to fragment and fall as large discrete clumps. These clouds can condense from a hot halo owing to thermal instabilities, losing angular momentum and falling into the SMBH on timescales of $\sim 10^5$ yr (Gaspari et al. 2013; King & Nixon 2015).

(c) Sharply truncated accretion disk: Inayoshi & Haiman (2016) suggest, based on nuclear starburst (SB) models (Thompson et al. 2005), that the growth of an SMBH over a few $\times 10^{10} M_\odot$ is stunted by small-scale physical processes. If a high accretion rate is achieved, vigorous star formation in the inner $\sim 10$–$100$ pc would be able to deplete most of the gas, causing the accretion rate to decrease rapidly (factor of $100$–$1000$).

In general, it remains unclear whether the main driver of the variability is the fueling mechanism at large scales or instabilities in the accretion disk.

We further compare our results to the framework for AGN variability presented by Sartori et al. (2018), which links the variability over a wide range of timescales. We calculate the total variability for the AGN in NGC 5972 as the difference between the apertures closest and farther from the center, which translates into a magnitude difference ($\Delta m = 9.8$) at a given time lag ($\tau = 5 \times 10^4$ yr; Equation (1) in Sartori et al. 2018). We compare this value with the structure function (SF; Figure 2 in Sartori et al. 2018) and find that our results fall within the Voorwerpjes region in the SF. The Voorwerpjes cover a range of $\Delta m$ from $\sim 6 \times 10^{-1}$ to $6 \times 10^1$ and of time lags of $\sim 10^5$–$10^6$ yr. The total variability of NGC 5972 falls well into this region with $\Delta m = 9.8$ and time lag $= 5 \times 10^4$ yr.

Furthermore, we calculate the $\Delta m$ for the entire light-travel time along the cloud, calculating the magnitude difference between each radius ($r_i$) with the following ($r_{i+1}$), and obtain a distribution of the SF from light-curve simulations in Sartori et al. (2018), as can be observed in Figure 26. Noticeably, this distribution fills a gap between data points from optical changing-look quasars, quasar SF, and Voorwerpjes derived from different methods.

5. Summary and Conclusions

In this work we present integral field spectroscopic VLT/MUSE observations for the nearby active galaxy NGC 5972, which shows a prominent EELR. The combination of the uninterrupted presence of ionized gas from the nucleus out to $\sim 17$ kpc and the spatial resolution and coverage of the MUSE observations have allowed us to study in detail the characteristics of this object. Our findings can be summarized as follows:

1. We detect an EELR that extends over $\sim 11$ kpc with a fainter tidal tail that extends between 11 and 17 kpc. The morphology of this region resembles a double-helix shape with highly filamentary structure. The analysis of the gas excitation through BPT diagnostic diagrams of this emission-line region shows that it is consistent with AGN photoionization.

2. The kinematics as disclosed by the emission lines shows a complex scenario, with multiple components as evidenced by the PVDs and the broad, often double-peaked spectral
profiles. We find evidence for a component that indicates disk rotation. The offsets from the systemic velocity are higher in the arms, reaching 300 km s\(^{-1}\) on the SE and NW regions, as compared to the disk rotation that reaches velocities of only \(\sim 120\) km s\(^{-1}\). These features can be interpreted as extraplanar gas connected to the tidal debris. A final component is observed as a kinematically decoupled inner disk, in the inner 6″, which contains an outflow along the minor axis reaching \(\sim 180\) km s\(^{-1}\) and appears to be dragging gas rotating in the large-scale disk.

3. The faint tidal tails of ionized gas observed in the NE and SE can also be a hint of a past merger event. EELRs are often associated with events of this type, as a merger can create tidal tails that are then illuminated and ionized by the AGN.

4. We use the photoionization code CLOUDY to generate a grid of models covering a range of ionization parameter and hydrogen density values, which we then fit to each aperture of an array that covers between 1 and 17 kpc of the extended ionized gas. The bolometric luminosities derived from this analysis for each radius along the arms show a systematic decrease with radius from the center. This suggests a decrease in AGN luminosity for model 1 (gas density derived from [S II] line ratio) between 40 and 120. For model 2 (gas density fitted with CLOUDY) the difference is between 80 and 160 times over the past \((3–5) \times 10^5\) yr. These variability amplitudes and timescales are in good agreement with previous luminosity history analyses (e.g., Lintott et al. 2009; Keel et al. 2012; Gagne et al. 2014) and AGN variability models (e.g., Sartori et al. 2018).

The extension of the ionized cloud in NGC 5972 makes it an ideal laboratory to carry out a comprehensive tomographic analysis of its EELR. It allows us to probe the AGN variability over a continuous \(10^5–10^6\) yr timescale, due to the light-travel time. This timescale is significantly larger than human timescales, and therefore it provides a unique opportunity to fill in the timescale gap for studies of AGN variability at different timescales (e.g., Sartori et al. 2018). The dramatic change in luminosity observed in the AGN of NGC 5972, as well as in other similar objects (e.g., Lintott et al. 2009; Gagne et al. 2014; Keel et al. 2017), suggests a connection to similarly dramatic changes in the AGN accretion state. The results presented are consistent with the scenario described in Schawinski et al. (2015), where AGN duty cycles \((10^7–10^9\) yr) can be broken down into shorter \((10^5–10^6\) yr) phases. To probe for longer timescales, larger extensions of ionized gas and larger FOV coverage with MUSE would be required.

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Appendix A

Nuclear Outflow

We perform a two-component Gaussian fit to the spaxels in the central 2\" area, where we observe an outflow. The velocity maps and example spectra for each component (narrow and broad) are shown in Figure 27. The outflow is extended along PA \sim 100\°, which corresponds to the minor axis of the large-scale rotation. The flux is obscured to the E side as shown by the magenta contours that mark the extinction. Red- and blue-shifted velocities are observed in both the narrow and the broad component, with the broad component reaching larger velocities. The observed velocities, however, are asymmetric, with the blueshifted region reaching velocities of 90 and 180 km s\(^{-1}\) for the narrow and broad components, respectively. The redshifted region shows velocities near systemic and 50 km s\(^{-1}\) for the narrow and broad components. The outflow seems to extend along the same axis of the radio lobes (Condon & Broderick 1988). It is possible that, at least partially, the receding outflow lies behind the galactic disk. Therefore, it could be affected by the extinction on the disk. In this scenario, the approaching section of the outflow would be, at least partially, above the disk in our line of sight. The velocity profiles extracted along PA = 110\° for both components (Figure 28) show that both follow similar patterns, with the broad component reaching larger velocities; therefore, it is possible that the main component of the outflow, represented by the broad component, is dragging along at least part of the gas that follows the main-disk rotation.

Appendix B

Metallicity

The metallicity chosen for our final CLOUDY models comes from creating a grid of models with different solar metallicities. In Figure 29 we show examples for an example aperture along arms “A” and “AT,” show solar and 1.5 times solar metallicities, and our custom metallicity where we only changed N and S elements based on their positions on the BPT diagram; these two elements were scaled 1.5 and 1.2 times their solar value. As can be observed in Figure 29, for apertures in arm “A” (and the same is true for arms “B” and “C”), a simple increase or decrease of solar metallicity was not enough to achieve a good enough fit, which is why we opted for scaling N and S. However, for arm “AT” this change resulted in a worse fitting, which is why we decided to maintain the metallicity as solar. Is important to remark that this change in metallicity kept very similar results for the \(U\) value obtained but changed the density (as can be observed in Figure 23), a problem we avoid by assuming the density obtained directly from the \([S II]\) ratio in model 1.
Figure 29. CLOUDY model over data ratios for the emission lines; solid lines show the model obtained assuming a density from the $[S\ II]$ emission-line ratio, while dashed lines show a model assuming the density as a free parameter. The top panel corresponds to an aperture over the “A” arm, while the bottom panel shows an aperture over the “AT” arm.

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