The origin of gas in extended narrow-line regions of nearby Seyfert galaxies – I. NGC 7212

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ABSTRACT
The extended narrow-line region (ENLR) of an active galactic nucleus (AGN) is a region of highly ionized gas with a size of a few up to 15–20 kpc. When it shows a conical or biconical shape with the apexes pointing towards the active nucleus, this region is also called an ionization cone. Ionization cones are evidence of the unified model, which predicts an anisotropic escape of ionizing photons from a nucleus confined to a cone by a dusty torus. Many details about the complex structure of the ENLR still remain to be unveiled, such as for example the origin of the ionized gas. Here we present new results of a study of the physical and kinematic properties of the circumnuclear gas in the nearby Seyfert 2 galaxy NGC 7212. Medium- and high-resolution integral-field spectra and broad-band photometric data were collected and analysed in the frame of an observational campaign of nearby Seyfert galaxies, with the aim of handling the complicated issue of the origin of gas in the ENLR. This work is based on (i) the analysis of gas physical properties (density, temperature and metallicity), (ii) the analysis of emission-line ratios and (iii) the study of kinematics of gas and stars. By reconstructing the [O III]/Hβ ionization map, we point out for the first time the presence of an ionization cone extended up to about 6 kpc, made of a large amount of low-metallicity gas, kinematically disturbed and decoupled from stars, a highly ionized component of which shows radial motions at multiple velocities, as proved by the complex profiles of the spectral lines. Since NGC 7212 is a strongly interacting triple galaxy system, gravitational effects are likely to be at the origin of the ENLR in this Seyfert galaxy.

Key words: line: profiles – techniques: spectroscopic – galaxies: individual: NGC 7212 – galaxies: Seyfert.

1 INTRODUCTION

Ionization cones are evidence of the validity of the unified model (Antonucci 1993), which postulates an anisotropic escape of photons from active galactic nuclei (AGNs) confined to a cone by a dusty torus. Up to now, a bright extended narrow-line region (ENLR) has been found in only 25 galaxies. Many details about the complex structure of the ENLR still remain to be unveiled. The small number of ionization cones could be related to the still-open problem of the origin of the ionized gas in ENLRs. In fact, ENLR gas could be part of the interstellar medium (ISM) of the host galaxy, photoionized by the active nucleus, or material ejected by the nucleus in strong interaction with a radio jet. Otherwise, the gas could be acquired from the intergalactic medium if the galaxy is in a dense environment, or by means of gravitational interactions in the case of minor merger events. This issue is strongly related to the mechanisms of AGN feeding.

Within this framework, we are carrying out an observational programme taking advantage of the integral-field spectroscopic technique to investigate the physical and kinematic properties of the ENLRs in a few nearby Seyfert 2 galaxies (z < 0.03) with possible ionization cones or at least extended [O III] emission. Here we present new results of the first studied object, NGC 7212.

NGC 7212 (z = 0.0266) is a Seyfert 2 galaxy in an interacting system of three galaxies (Wasilewski 1981). Durret & Warin (1990), by means of optical long-slit spectroscopy in the Hβ + [O III] spectral range, found ionized gas extending for ~17 arcsec along position angle PA = 37° and 127°, and a high excitation value R = I([O III])λ 5007+4959/I(Hβ) = 19 in the nucleus, ranging from 5–28 in the
ionized emission. Tran (1995) detected a jet-like highly ionized feature extended up to 10 arcsec from the nucleus at PA = 170° in ground-based [O iii] and Hα images. This feature is exactly parallel to the axis of the small-scale double radio source (0.7 arcsec separation) published by Falcke, Wilson & Simpson (1998), who did not find clear evidence of an ionization cone. Kotilainen (1998) published the $B - I$ map of NGC 7212 showing a very blue and fan-shaped emission region extending from the nucleus towards the south (PA = 165°) with a total size of 2.3 arcsec and a dust lane situated on the other side of the nucleus at 3.7 arcsec and PA = 280°. Hubble Space Telescope (HST) [O iii] images by Schmitt et al. (2003) showed that the [O iii] emission is extended up to ~3 arcsec from the nucleus along PA = 170° with dimensions 2.1 × 4.8 arcsec$^2$. The emission is diffuse and composed of several individual knots northwards and southwards of the nucleus. Raimann et al. (2003) found that the nuclear stellar component of NGC 7212 is dominated by a 10-Gyr metal-rich (solar or above solar metallicity) stellar population, with a contribution of 15 per cent of the total flux from the 1-Gyr component and 15 per cent from the 3-Myr component or from a featureless continuum. Bennert et al. (2006) confirmed the [O iii] emission along PA = 170°, but extended up to 12 arcsec from the nucleus, i.e. four times larger than the extension seen in the HST image in the same direction but smaller than the maximum extent reported by Durret & Warin (1990), who observed at different position angles. The reddening-corrected excitation value in the central spectrum is $R \sim 16$ and varies between 6 and 17 in the central 24-arcsec-wide region. The reddening in the centre is rather low ($E(B - V) = 0.33 \pm 0.01$ mag) and decreases to a value of ~0.07 mag at 1 arcsec north-west of the nucleus. On both sides of this region, it increases and reaches its maximum value at 4 arcsec south-east and 7 arcsec north-west of the photometric centre ($\Delta E(B - V) \sim 1$ mag). These maxima may be attributed to dust lanes seen in the continuum image by Falcke et al. (1998).

## 2 OBSERVATIONS AND DATA REDUCTION

NGC 7212 was observed at the Russian 6-m telescope of the Special Astrophysical Observatory (SAO RAS) with the Multi Pupil Fiber Spectrograph (hereafter MPFS; Afanasiev, Dodonov & Moiseev 2001). This integral-field unit takes simultaneous spectra from 256 spatial elements; the field of view (FoV) is 16 arcsec$^2$ with a spatial sampling of 1 arcsec. Spectra of NGC 7212 were obtained in 2005 September in the range 3800–7300 Å with a 600 line mm$^{-1}$ grating, and in 2007 July in the range 4000–7300 Å with a 1200 line mm$^{-1}$ grating. The data have a dispersion of 1.5 and 0.8 Å pixel$^{-1}$ and an instrumental resolution of ~6 and ~3 Å, respectively. NGC 7212 was also observed with the high-resolution ($R \sim 8000$) MagE echelle spectrograph at the Magellanic Telescopes of the Las Campanas Observatory (Chile), with the slit oriented along the ionization cones (PA ~ 170°). From the HST–MAST archive, a Wide-Field Planetary Camera 2 (WFC2) image in the F606W broad-band filter was extracted. Broad-band BV images were obtained in 2008 September at the SAO 6-m telescope with SCORPIO (Afanasiev & Moiseev 2005) (Fig. 1). All the observational and archival data are listed in Table 1, where $\Delta \lambda$ is the spectral resolution in Å and $\delta \lambda$ is the dispersion in Å pixel$^{-1}$.

The MPFS data were reduced using v30 (Sandin et al. 2010), which is a general data-reduction software written in the IDL language and developed to work with fibre-fed integral-field units (IFU) of any integral-field spectrograph. Up to now, it has been configured and tested with Potsdam Multi-Aperture Spectrophotometer (PMAS), Visible Integral-field Replicable Unit Spectrograph Prototype (VIRUS-P), Segmented Pupil/Imaging Array Lenses (SPIRAL) and MPFS. v30 makes the reduction steps up to wavelength calibration automatically, and allows us to inspect and optimize parameters interactively when required. It also provides graphical tools to check the raw data and the output of the different tasks. In order to perform the flux calibration, we observed a spectrophotometric standard star for each run. Its spectra were extracted, flat-fielded and wavelength-calibrated with v30, then sky-subtracted and summed together with IRAF to collect the total flux. The usual IRAF tasks for the flux calibration were applied to the data. The echelle spectrum was reduced with IRAF following the standard procedures (bias-subtraction, flat-field correction and wavelength calibration). No other calibrations or corrections were applied. Before reducing this spectrum, the orders were extracted using APALL with the option strip.

After the reduction procedures, the IFU spectra were corrected for Galactic reddening using the IRAF task $\text{deredden}$ and the value of V-band absorption ($A_V = 0.238$) derived from the NASA/IPAC

![Figure 1. R-band image of NGC 7212 obtained at the SAO 6-m telescope with SCORPIO. The white (black) square is the MPFS FoV for the low-(high-) resolution data. The FoV is 16×16 arcsec$^2$, corresponding to 8.2 × 8.2 kpc$^2$ (scale = 0.513 kpc arcsec$^{-1}$, $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$). North is up and east is to the left.](https://academic.oup.com/mnras/article-abstract/418/4/2630/1028933)
Extragalactic Database (NED), then we corrected for telluric absorption. In fact, at $z = 0.0266$ the [S II] doublet falls in the range 6880–6930 Å, and therefore it is only partially absorbed by the atmospheric $B$ band (6860–6890 Å). We used two IRAF scripts, ATMO and RMAT, written by our group. ATMO fits the continuum of the flux-calibrated standard star and divides the fitting by the stellar spectrum. Then, all intensity values at $\lambda$ shorter than 6700 Å are put equal to 1. Finally, the corrected spectrum is obtained using the task RMAT, which simply multiplies the observed spectrum by the output of ATMO. We also applied a correction for atmospheric refraction. We used two IRAF scripts written by us, named ACORR and DARCSPEC. The first task determines the correction to apply for atmospheric refraction, the second one applies this correction. In particular, ACORR creates images of the emission for 20–30 intervals centred at different $\lambda$ along the dispersion direction, then it calculates the centroid of each image using IMCENTROID and allows us to fit interactively with a straight line the relations $\lambda$ versus $x$ and $\lambda$ versus $y$, using NIFT1D. DARCSPEC uses the $x(\lambda)$ and $y(\lambda)$ functions and for each $\lambda$ along all the spectral range it makes an image, applies the needed shift (taking as a reference the centroid at $\lambda = 5500$ Å) and then transforms the image into a table with three columns: $x$, $y$, $\lambda$. From these output tables the spectrum corrected for atmospheric refraction is reconstructed.

In order to measure the emission lines accurately, in particular hydrogen and helium Balmer lines, the underlying stellar component was subtracted from the spectra. We applied the STARLIGHT software (Cid Fernandes et al. 2005, 2007) to fit the galactic stellar component. Before being analysed with STARLIGHT, the spectra were shifted to rest-frame wavelengths with NEWREDSHIFT and their dispersion was modified to a value of 1 Å pixel$^{-1}$ with DISCOR. We used 45 synthetic spectra by combining 15 ages (from $10^7$–$13 \times 10^7$ yr) with three metallicities ($Z = 0.004$, 0.02 and 0.05 $Z_\odot$) and the Cardelli, Clayton & Mathis (1989, hereafter CCM) extinction function. The synthetic spectrum of the stellar contribution obtained from STARLIGHT for each fibre was subtracted from the observed one to obtain a pure emission-line spectrum. These procedures were performed only for low-resolution spectra, because high-resolution data were used only to study the kinematics. Moreover, in high-resolution spectra the Balmer absorption lines could be neglected because of the low signal-to-noise ratio (S/N, less than 5) of the continuum.

For the analysis of IFU data, we used Peak ANalysis (PAN), an IDL software that fits emission lines with a graphical interface, based on the MPFIT of Craig Markwardts. We applied a single Gaussian function for all the emission lines except H$\alpha$ + [N II] and [S II], for which we used custom functions that allowed us to fit all the lines simultaneously. PAN is useful for integral-field data since it can read multiple spectra and fit the initial guess to all the spectra automatically. The spectrum, fitting and residuals can be reviewed, being displayed on-screen. The initial parameters (amplitude, position and width) can be specified interactively and constrained to ensure a reasonable result: it is possible to fix to the same value the full width at half-maximum (FWHM) of the doublets like [N II] and [S II]. For the high-resolution data of NGC 7212 we used the MIDAS package XALICE because it was necessary to fit the [O III] emission lines with two components, a broad and a narrow one.

The reliability of our measurements was verified by calculating the S/N of the continuum for MPFS data (see Fig. 2). These data have small values of S/N: the median value for low-resolution data are $\sim 5.6$ and $\sim 5.4$, measured at rest-frame 5500 and 7000 Å. The $\chi^2$ evaluates the quality of the STARLIGHT fitting: it is peaked around 1.6 (see Fig. 2) instead of 1, probably because the S/N ratio of the analysed spectra is not sufficiently high. We calculated the flux errors, assuming that the determination of the position of the continuum level gives the main contribution to the errors when measuring the emission-line fluxes.

### 3 Physical Properties of Gas and Stars

All the measured fluxes were corrected for internal reddening, using the Balmer decrement and assuming a theoretical value of the intensity ratio between H$\alpha$ and H$\beta$ equal to 2.86. The visual absorption, $A(V)$, was estimated by applying the CCM extinction law. Once we obtained $A(V)$, we corrected all the observed fluxes. In order to study the spatial distribution of the extinction, we reconstructed the $A(V)$ map (see Fig. 3), which is clearly limited to the region where the H$\beta$ emission line can be measured. In the nucleus the reddening is low, $A(V) = 0.78$ mag, while higher values, $A(V) = 1.6$–2 mag, are found at about 7 arcsec north-west and at about 4 arcsec east of the nucleus, in agreement with the reddening obtained by Bennert et al. (2006), $E(B - V) = 0.33$ mag in the centre and $E(B - V) < 0.8$ mag in the north-western and south-eastern regions (see their fig. 3, upper right panel). We estimated the extinction from the stellar spectra by means of STARLIGHT, which also gives as output the $A(V)$ values for each spectrum. By comparing the $A(V)$ obtained from gas and stars, we can see that the distributions are peaked at different values, larger for the gas: the median value for gas is 1.38 mag and that for stars is 0.68 mag. If the ENLR gas were dust-free, then the $A(V)$ measured by stars and gas would be the same. The larger extinction observed in the gas component suggests that there is also a fraction of dust associated with the ENLR.

![Figure 2](https://academic.oup.com/mnras/article-abstract/418/4/2630/1028933)

**Figure 2.** Left: S/N of the IFU low-resolution data measured at 5500 Å (solid line) and at 7000 Å (dashed line). Right: histogram of $\chi^2$, evaluating the quality of the STARLIGHT fitting.

![Figure 3](https://academic.oup.com/mnras/article-abstract/418/4/2630/1028933)

**Figure 3.** Left: $A(V)$ map, obtained by applying the CCM extinction law to the ratio of intensity of H$\alpha$ and H$\beta$, with the stellar continuum contours overlaid (in black). Right: The histogram of the $A(V)$ values obtained for gas (solid line) and stars (dashed line).
Up to 30 emission lines were detected and measured, at least in the central regions, within a radius of about 4 arcsec. The maps of the brightest emission lines ([O\text{\textsc{iii}}] \lambda 5007, [O\text{\textsc{iii}}] \lambda 5007, [O\text{\textsc{ii}}] \lambda 6300, [N\text{\textsc{ii}}] \lambda 6548, H\alpha \lambda 6563, [N\text{\textsc{ii}}] \lambda 6584, [S\text{\textsc{ii}}] \lambda 6716, [S\text{\textsc{ii}}] \lambda 6731) show an elongated shape: the ionization gas is extended up to 15 arcsec (corresponding to \(~\sim\)7.7 kpc, scale = 0.513 kpc arcsec\(^{-1}\)) with a PA \(\sim 0^\circ\). A similar size was detected by Durret & Warin (1990) with long-slit spectroscopy. They found ionized gas extending for about 17 arcsec at PA = 37\(^\circ\) and PA = 127\(^\circ\), corresponding to the minor and major axis of the galaxy, respectively. We verified that this emission is within our FoV. Bennert et al. (2006) found ionized gas extending out to 12 arcsec along a PA \(\sim 170^\circ\). The emission is not oriented as the stellar continuum emission, which has the major axis at PA = 45\(^\circ\); in Fig. 4 the [O\text{\textsc{iii}}] and H\alpha emission-line maps are shown with the contours of the stellar continuum emission at 5500 Å overlaid. We compared our emission-line maps of [O\text{\textsc{iii}}] and H\alpha with the images published by Tran (1995). Fig. 5 shows a good match between the contours of these images and our two-dimensional (2D) maps. [O\text{\textsc{iii}}] \lambda 4363 and He\text{\textsc{ii}} \lambda 4686 maps are clearly elongated as well, with PA \(\sim 0^\circ\) and extended up to 9–10 arcsec (corresponding to \(~\sim\)4.5–5 kpc). Fainter emission lines are visible not only in the very inner region, where the influence of the ionization source is more important, but also at 3–6 arcsec (1.5–3 kpc) from the nucleus. The coronal emission lines of iron with different ionization degree were detectable as well and were measured, but only in the central spectra, probably because here both the ionization and the S/N are sufficiently high. We detected [Fe\text{\textsc{ii}}] \lambda 4658, [Fe\text{\textsc{v}}] \lambda 4228, [Fe\text{\textsc{vi}}] \lambda 5158 and [Fe\text{\textsc{vi}}] \lambda 5721 and [Fe\text{\textsc{vi}}] \lambda 6087 (Fig. 6).

We calculated the density with the TEMDEN IRAF task, by using both the [S\text{\textsc{ii}}] \lambda 6716/6731 and [Ar\text{\textsc{iv}}] \lambda 4711/4740 ratios. The [S\text{\textsc{ii}}] and [Ar\text{\textsc{iv}}] lines have different values of critical density (log \(N_e\) = 3.2, 3.6, 4.4 and 5.6, respectively), thus we can assume that these lines are emitted by gas in different physical conditions. The [Ar\text{\textsc{iv}}] ratio gives information about higher density and higher ionization gas, while lower density gas can be studied by means of the [S\text{\textsc{ii}}] ratio. We used an input value of temperature \(T = 10^4\) K and we calculated the density for each spectrum in which we measured these ratios. Unfortunately, the [Ar\text{\textsc{iv}}] lines could be measured for a few central spectra only, which did not yield significant information about the spatial distribution of the high-density gas. Therefore we calculated the density using the [S\text{\textsc{ii}}] doublet, which is detectable in a more extended region, finding a median value of \(~\sim\)450 cm\(^{-3}\) (see Fig. 7). The central density obtained with [Ar\text{\textsc{iv}}] is \(~\sim\)2.2 \times 10\(^6\) cm\(^{-3}\) (assuming \(T_e = 10^4\) K) and is in good agreement with the value obtained with [S\text{\textsc{ii}}] \(~\sim\)1.4 \times 10\(^4\) cm\(^{-3}\). These higher values of density (1–1.4 \times 10\(^3\) cm\(^{-3}\)) are in an internal region oriented roughly east–west. Bennert et al. (2006) also estimated high density values (\(\sim\)10\(^3\) cm\(^{-3}\)) within an aperture of 2 arcsec at the nucleus (see Fig. 7).
their fig. 6, upper right panel). The gas temperature was obtained by calculating the ratio between the flux of [O III] λλ 4959+5007 and [O II] λ 4363, and by calculating the ratio between the flux of [S II] λλ 6717+6731 and [S II] λ 4068+4076. We determined the temperature with these two ratios, in cases where the λ 4363 and λ 4068+4076 lines could be measured. We derived the temperature using TEMDEN and the values of density calculated with the [S II] ratio. The histograms for the two determinations of temperature are shown in Fig. 7. The median values are 1.8 × 10^4 K and 1.5 × 10^4 K for [O III] and [S II] ratios respectively. For high-ionization gas, we should calculate the density using high-ionization doublets, but in this case we detected the [Ar IV] emission lines in the inner parts only, and we could estimate the density using this ratio only for a few nuclear regions. Thus we used the [S II] density determination for the temperature estimate with the [O III] ratio. Higher values (up to 2–3 × 10^4 K) were found in the northern part of the FoV, while in the central regions we measured lower values (1–1.5 × 10^4 K) with [O III], and lower still with [S II] (4–9 × 10^3 K).

In the case of ionization by a power-law spectrum, as for an AGN, the determination of the metallicity is complicated because the ionization structure can be complex. There are not direct methods to determine the metallicity, and comparison with photoionization models must be used. To estimate the gas metallicity, we compare the measured fluxes with CLOUDY models from Vaona (2010), using the emission-line ratios [N II] λ 6584/[O III] λ 3727 versus [N II] λ 6584/[S II] λ 6724. Vaona showed that this diagram is sensitive to metallicity. The models have a low resolution in metallicity because he used few Z/Z⊙ values; nevertheless, the trend is clear. We used models with dust-to-gas ratio (D/G) equal to 1. The plot and the comparison between the observed values and the theoretical models allowed us to estimate a subsolar metallicity for the ionized gas in NGC 7212 (see Fig. 8).

From the STARLIGHT output, we reconstructed 2D maps of the stellar velocity field, as well as 2D maps of the distribution of the stellar population with different ages and metallicities. The maps were built using only the models in which the adev parameter was less than 50 per cent. This parameter is an output of STARLIGHT and corresponds to the average percentage value (Oi - M_i)/Oi of the deviation between the observed spectrum (Oi) and the modelled one (M_i) over all fitted pixels. Then we selected only the spectra with S/N > 3. We obtained the flux distributions for stellar populations in different ranges of age: young (t < 10^8 yr), medium (10^8 < t < 10^9.5 yr) and old (t > 10^9.5 yr); and with different metallicities: subsolar (Z = 0.004), solar (Z = 0.02) and supersolar (Z = 0.05). We created the B − R colour image from the broad-band images obtained at SAO and compared it with the 2D maps showing the stellar population distribution. The colour image (Fig. 9, bottom right panel) shows a red ring-like structure north and north-west of the nucleus, corresponding to the large dust lane already visible in the broad-band images and in our A(V) map, and a blue region south-east of the nucleus. Both these structures were detected by Kotilainen (1998), who found a blue fan-shaped region along PA = 165° extended for about 2.3 arcsec. Our region has the same size but its shape is circular due to our seeing of about 1.5 arcsec, worse than the 0.7-arcsec seeing in the Kotilainen images. As in Raimann et al. (2003), we found that the old population (t > 10^9.5 yr) is the main component and in the nucleus we also found a younger component (10^8 < t < 10^9.5 yr). In particular, in a large ring-like structure 70–80 per cent of the total light is due to the old stellar population. A lower percentage of the light (50–60 per cent) is observed in a central elongated region oriented at PA = 90°, where the intermediate-age population accounts for 30–40 per cent of the total. This apparent hollow in the distribution of the light of old stars is simply an effect of the presence of younger stars with smaller MIL ratio. Finally, about 10 per cent of the light seems to be emitted by a young population, but we stress that it could be an effect of diffuse light from the cone and scattered light from the AGN. In fact, STARLIGHT does not distinguish between the OB-star contribution and a power-law continuum. Therefore, even if in a Seyfert 2 galaxy the AGN

Figure 8. The graph of log ([N II]/[S II]) versus log ([N II]/[O III]) compared with theoretical models by Vaona (2010) with D/G = 1. The observed values are black crosses.

Figure 9. Top: 2D maps of the old (left) and medium-age (right) stellar population. Bottom: 2D map of the young population (left) and the B − R colour (right). The cross is the position of the galaxy nucleus. North is up and east is to the left.
continuum is strongly absorbed with respect to Seyfert 1s, detection of a young and very young population could be wrong, due to contamination from the AGN featureless continuum. In addition, a high proportion of the intermediate stellar population is found in the interaction regions (north-east of the nucleus). This component could result from the ongoing merger.

We used the diagnostic ratios applied in the BPT and VO diagrams (Baldwin, Phillips & Terlevich 1981; Veilleux & Osterbrock 1987) to investigate the ionization mechanisms acting in the ENLR. The 2D maps of the diagnostic ratios are shown in Fig. 10. The [NII]/Hα, [OIII]/Hβ and [SII]/Hα maps were created using non-reddening-corrected values, in order to study a more extended field that is not limited by the small size of the Hβ emission. From the 2D maps, we detected for the first time an extended structure with high values of [OIII]/Hβ, greater than 10, suggesting the possible presence of an ionization cone oriented like the galaxy minor axis (see Section 5). The [OIII]/Hβ ionization map shows high values even far from the nucleus. If photoionization is the only ionization mechanism then the photon flux is diluted with increasing distance and it is not expected to remain high at large distance from the nuclear source. We speculate that this could be a density effect: in fact the ionization parameter \( U = Q_{\text{ion}}/(c^2N_{\text{H}}) \), where \( Q_{\text{ion}} \) is the number of ionizing photons per second emitted by the source, depends on both the inverse of density and the distance. Therefore,
high values of $U$ could be due to high values of ionizing photon flux or to low density. Inside the cone we found low density, but without a gradient; the value is approximately the same along the whole cone. Thus, we can exclude the suggestion that high values of $U$ are due to low density. We can invoke the presence of shocks as an additional mechanism of ionization. Indeed, some regions inside the cone show electron temperature values larger than $3 \times 10^4$ K, suggesting that shocks could be at work. However, this hypothesis will be tested with photoionization+shocks models (Contini et al., in preparation).

In addition, according to the very high values of $[O\text{ III}]/H\beta$, we can also exclude a contribution from star formation. The diagnostic ratios of $[N\text{ II}]/H\alpha$ and $[S\text{ II}]/H\alpha$ are not smoothly distributed, showing higher values (respectively $\sim 1$–1.3 and $\sim 0.7$–0.9) orthogonal to the cone and outside it. Furthermore, these ratios show higher values in the north-eastern regions, namely in the interacting regions between the two galaxies, as clearly seen in Fig. 10 with the galaxy contours overlaid. Here the ratios can be strongly influenced by interaction effects, such as shocks. The $[O\text{ I}]/H\alpha$ map is peculiar. It shows an elongated shape along the galaxy major axis, with high values oriented similarly to the high-density structure. High values of $[O\text{ I}]/H\alpha$ are related to collisions. The $[O\text{ I}]$ emission line is formed in the recombination region, where O$^+$, H$^+$ and H exist. This region is more extended if the ionizing source has a power-law spectrum. This ratio is very useful to distinguish between photoionization by AGN and stars. We plotted the VO diagnostic diagrams, using the reddening-corrected fluxes, for regions both inside and outside the ionization cones (see Fig. 11). In order to separate the different regions in the diagnostic diagram (AGN, H II regions and LINERS), we used the expressions from Kewley et al. (2006). By analysing these diagrams, we noticed that all regions occupy the AGN area and are distributed vertically towards the shock region. This means that for each region, inside and outside the cone, the ionizing source has a power-law spectrum. The only difference is that for the regions outside the cone the ionization decreases with increasing radius, whereas inside the cone it also remains high far from the nucleus. Possible explanations are that the ionizing photons from the cone are diffused or that the cone aperture angle is larger.

4 KINEMATICS

For the main emission lines, we also built 2D maps of velocity and FWHM (see two examples for $[O\text{ III}]$ and $H\alpha$ in Fig. 12). The measured velocities were corrected for the systemic velocity, considering the value obtained from the nuclear spectrum, i.e. the spectrum with the highest flux in the continuum map. For each spectrum the mean instrumental FWHM, obtained by fitting a few lines of the comparison lamp, was subtracted quadratically from the measured values, in order to take into account differences of the instrumental resolution in the field. The maps of the velocity field show values ranging from $-180$ km s$^{-1}$ to $+150$ km s$^{-1}$ for $[O\text{ III}]$ and from $-220$ km s$^{-1}$ to $+180$ km s$^{-1}$ for $H\alpha$. The maps of the FWHM, after the correction for instrumental width, show values between $200$ km s$^{-1}$ and $800$ km s$^{-1}$ for both $[O\text{ III}]$ and $H\alpha$ lines. The velocity maps show distortions east of the nucleus, especially in case of $H\alpha$, $[N\text{ II}]\lambda 6548,6584$ and $[S\text{ II}]\lambda 6717,6731$ lines, while the $[O\text{ III}]\lambda 5007$ line shows a more regular pattern. In particular, the $H\alpha$ velocity map in the eastern region has velocity values between $130$ km s$^{-1}$

![Figure 11](https://academic.oup.com/mnras/article-abstract/418/4/2630/1028933)

**Figure 11.** The VO diagnostic diagrams. The squares are regions inside the cone, the triangles are regions outside.

![Figure 12](https://academic.oup.com/mnras/article-abstract/418/4/2630/1028933)

**Figure 12.** Left: 2D maps of flux (top), velocity (middle) and FWHM (bottom) for high-ionization gas ($[O\text{ III}]$). Right: the same for low-ionization gas ($H\alpha$).
and 200 km s$^{-1}$. This zone appears to be located towards the interaction region. Its high FWHM values (300–600 km s$^{-1}$) could be an effect of the gravitational interaction between NGC 7212 and its companion galaxy. However, in the HST image and in the SAO broad-band image and colours, this region shows no particular structure and has a low surface brightness ($10^{-16}$–$10^{-15}$ erg cm$^{-2}$ s$^{-1}$). In the $[\text{O III}]$, $[\text{O I}]$, $[\text{N II}]$, H$\alpha$ and $[\text{S II}]$ FWHM maps it is clearly visible as an elongated structure with higher values, up to 700–800 km s$^{-1}$, oriented at about 90$^\circ$ with respect to the major axis of the emission.

The FWHM of $[\text{O III}]$ published by Durret & Warin (1990) ranges from 320–385 km s$^{-1}$. This disagreement is likely due to the orientations of the slit, which do not correspond to this elongated structure. In any case, we observed values between 500 and 600 km s$^{-1}$ in the nuclear region. This feature has been already observed in other Seyfert galaxies, like Mrk 3 (Di Mille 2007), Mrk 34, Mrk 1066, Mrk 348, Mrk 1, NGC 2992 and NGC 5728 (Stoklasová et al. 2009). The explanation for this effect is still under debate. This structure is also found when we fit the high-resolution $[\text{O III}]$ emission-line profile with two separate components. The minor axis of the stellar velocity field is aligned with the photometric minor axis, while in contrast the gas velocity field is rotated with respect to the stellar one (Fig. 13). From the analysis of the low-resolution data we can see that stars and gas are not aligned; the $[\text{O III}]$ emission is elongated along a direction orthogonal to the major axis of the galaxy. This could imply that the gas is not coplanar with the stars. It is interesting to comment that the jet-like structure studied by Tran (1995), extending up to about 10 arcsec, oriented at PA $\sim 10^\circ$ and showing a redshifted velocity of 180 km s$^{-1}$, is not consistent with material ejected by the nuclear source but instead is rotating ionized gas, as is clearly visible from our $[\text{O III}]$ velocity map.

The density map is aligned as the FWHM maps. By comparing the high-density ($N_e = 700–1400$ cm$^{-3}$) regions in the map with the FWHM maps (Fig. 14), we found high values of FWHM ($\sim 500$ km s$^{-1}$) in regions showing high density. These are hints of compressed gas, or streaming of gas, and can be consistent with shocks. The north-eastern region with higher FWHM and a peculiarity in the velocity field is near to the region of the merger between the galaxies and not connected to the ionization cone visible in the $[\text{O III}]/H\beta$ map. All the previous peculiarities could be caused by this interaction (see Fig. 14). From the analysis of the emission-line profiles it is possible to point out the presence of asymmetries that may be due to additional and non-rotational kinematic components. With the low-resolution data, we were not able to identify and analyse multiple components in the spectral line profiles, although some asymmetries in the line profile for higher S/N spectra were observed and as a consequence the fitting was more difficult to perform.

From the higher resolution IFU data, initially we fitted $[\text{O III}]$ and H$\alpha$ emission lines with a single component and built 2D maps of flux, velocity and FWHM. We used these maps as input for ROTCUR (Begeman 1989), the task of the Groningen Image Processing System (GIPSY) software, to model the 2D map and to obtain the deprojected values of the velocity in order to build the rotation curve. This task uses tilted-ring models: it models the velocity map using concentric rings and taking into account the inclination on the line of sight. Before starting, we needed to calculate the inclination angle ($i$) of the gas or stellar emission. We obtained $i$ by matching the distribution of $[\text{O III}]$ and H$\alpha$ emission with an ellipse. From this ellipse we also obtained the PA of the emission. We corrected the velocity maps for the systemic velocity, using the values obtained in the central spectrum, and finally we could run ROTCUR. We fixed the following input parameters: inclination ($i = 40^\circ$), which was the same for the $[\text{O III}]$ and H$\alpha$ maps, systemic velocity ($0.0$ km s$^{-1}$), expansion velocity ($0.0$ km s$^{-1}$) and coordinates ($x, y$) of the centre of the galaxy. The other input parameters were the radii of the concentric rings in arcsec, the first guess for the rotational velocity of each ring and the position angle, and we left them free. To begin with, we applied this task to the whole 2D velocity map, fitting both the approaching and the receding side at the same time. This output was used as input for the task VELFI, which reconstructs the model of the observed velocity field, and then we checked whether the model could reproduce the velocity map well. As an alternative, to obtain more accurate values of the deprojected velocity in order to build the velocity curve the velocity maps were fitted in two steps: first the receding and then the approaching side.

We compared the gas rotation curves with the stellar rotation curve obtained by applying ROTCUR to the stellar velocity map ($i = 54^\circ$, PA $\sim 45^\circ$). We found that the kinematic behaviour and the velocity values are similar for stars and gas. This implies that the kinematics of ENLR gas and stars are dominated by the same gravitational potential (see Fig. 15). However, looking at the 2D maps we have already seen that the kinematic axis of stars is inclined by about 30$^\circ$ with respect to that of gas (Fig. 13). This could be a projection effect: gas and stars could be distributed in a different way and in a different plane. Stars are in agreement with the continuum emission, while gas velocity maps are oriented according to the gas emission. We estimated the errors in velocity by measuring the position of some night-sky lines and assuming that the main contribution to the errors is that of wavelength-calibration errors. We found median values of 12 km s$^{-1}$ for $[\text{O III}]$ and 19 km s$^{-1}$ for H$\alpha$. No error is reported in the output of STARLIGHT for stellar kinematics.

In principle, we should take into account the S/N ratio of the emission lines (Corsini et al. 1999): when the S/N is high, the error is due only to errors in calibration, whereas when the S/N is low the error is due to the badly fitted line profile. In our case, the S/N of these emission lines is high over the whole field. The errors may be larger in the presence of asymmetries. For high-resolution data we also have the error due to the fitting of the two components. By assuming that gas and stars are on circular orbits in a plane, we can fit the rotation curves with the following formula (Bertola et al. 2009):
where \( A \), \( c_0 \) and \( p \) are parameters and \( r \) is the radius in arcsec. The \( p \) parameter is between 1 and 3/2. We fit the gas rotation curve using both \([\text{OIII}]\) and \( \text{H}\alpha \) (see Fig. 15) with \( A = 300 \text{ km s}^{-1} \), \( c_0 = 2.5 \text{ arcsec} \) and \( p = 1.1 \). The fitting of stellar and gas rotation curves shows good agreement. By assuming a spherical potential, we can infer the mass distribution \( M(r) \) using the virial theorem, considering as maximum extension \( r = 7 \text{ arcsec} \) (corresponding to 3.6 kpc). Within this radius, we found \( M = 4.45 \times 10^{10} \text{ M}_\odot \).

In order to perform a more accurate analysis of the kinematic behaviour of the ionized gas, we focused on the \([\text{OIII}]\) line of the higher resolution MPFS spectra. By using a multiple Gaussian fitting, we identified two kinematic components, a narrow and a broad, which suggests a complicated kinematic structure of the NGC 7212 ENLR. We decided to apply the \textsc{MIDAS} package \textsc{xalice}, which is more effective than \textsc{pan} in this case, and we obtained the flux, velocity and FWHM maps for both narrow and broad components (see Fig. 16). The two components have different velocities and different inclinations of the minor axis. For the narrow component we found values ranging between \(-120 \text{ km s}^{-1} \) and \(+170 \text{ km s}^{-1} \) and FWHM values up to 350–400 km s\(^{-1}\). The broader component shows lower velocity values, from \(-80 \text{ km s}^{-1} \) to \(+120 \text{ km s}^{-1} \), and FWHM up to 700–750 km s\(^{-1}\). We estimated \( \text{PA} = 130^\circ \) for the stellar map, \( \text{PA} = 97^\circ \) for the narrow \([\text{OIII}]\) component and \( \text{PA} = 140^\circ \) for the broad one. However, they are not aligned with the stellar velocity. The high-turbulence region observed in the single-fitting \([\text{OIII}]\) map and oriented like the minor axis of the gas emission is still present in both components.

Having found hints of multiple components in \([\text{OIII}]\) profiles, we decided to explore the gas kinematics by analysing a high-resolution echelle spectrum (\( R \sim 8000 \), instrumental FWHM \( \sim 0.85 \text{ Å} \)) obtained with the slit oriented along the ionization cones. By simply looking at the spectrum it is clear that the emission is due to various subcomponents at different velocities. We can see from Fig. 17 that the emission-line profile of \([\text{OIII}]\) is strongly variable and depends on the spatial position. Notwithstanding the high spectral resolution, the components of the emission-line profiles of the high-ionization gas are still broad, therefore we decided to analyse the lower ionization gas using the \([\text{Sii}]\) doublet, in which the emission lines are narrower and it is easier to identify and distinguish the different components. We found at least four components at different velocities (see Fig. 18): \( v_{11} \sim -300 \text{ km s}^{-1} \), \( v_{12} \sim -150 \text{ km s}^{-1} \), \( v_{13} = 0 \text{ km s}^{-1} \) and \( v_{14} \sim 170 \text{ km s}^{-1} \), for \([\text{Sii}]\) \( \lambda 6716 \). These components
and arcsec III component of [S] (Kennicutt 1998), = flux. × v ∼ B λ III v cm C images. The lower v II λ image of NGC 7212 it is clear that the ENLR is 10/Ω1 ∼ 450 km s ∼ × 10 II = α II [S ∼ erg s 10 HST L erg s where III III λ 2011 The Authors, MNRAS ratio without any reddening correction. The same side was HST 150 × cm λ arcsec − III The ionization map with the cone contours overlaid (left), the WFPC2 image of NGC 7212 (middle) and the same with the cone contours overlaid < cm v ∼ ratio III 2630–2641 of [S r R λ 2011 RAS on 30 July 2018 by guest Downloaded from https://academic.oup.com/mnras/article-abstract/418/4/2630/1028933 velocity components are blended in the broad [O II] which is not visible in the [S ions. From the ionization map we have detected an elongated and extended highly ionized structure with high values (10–14) of [O iii]/Hβ, up to 4 kpc from the nucleus, pointing out for the first time the presence of extended ionization cones in NGC 7212. In their spectra this ratio ranges from 5–28. The reddening-corrected value from Bennert et al. (2006) is ∼ 16 in the nucleus and varies between 6 and 17 in the central regions. Taking into account the [O iii] λ4959 contribution, we found [O iii]/Hβ = 16 in the nucleus, with values ranging between 12 and 19 at about 7 arcsec north-west of the nucleus and between 12 and 16 at about 5 arcsec south-east of the nucleus. We selected the spaxels of the cone considering only those showing [O iii]/Hβ > 8. The aperture angle of the cone is ∼ 70°. As we have already mentioned, this angle could be larger to account for the regions located far from the nucleus in a direction orthogonal to the cones, but showing AGN-like ionization. The cone has a total size of 12 arcsec, corresponding to ~6 kpc, and it is oriented at PA = 150°.

The FWHM of the ionized gas inside the cone is around 200–300 km s⁻¹. The density is <10⁵ cm⁻³, without a radial trend, in contrast to the results found by Dadina et al. (2010) in NGC 5252. These authors derived a r⁻² relation from the constant [O iii]/(0.5–2 keV) flux ratio, which suggests a radial independence of the ionization parameter. We observed a gradient of temperature, with higher values in the northern region. We plotted the [O iii]/Hβ ratio versus the distance from the nucleus, dividing the spaxels inside and outside the cone (Fig. 20). As expected, we found that outside the cone the ratio decreases with distance from the nucleus, while inside the cone the ratio is high even far from the nucleus (up to 4 kpc). In order to understand whether the AGN can account for such a high level of ionization, we made some energy-balance considerations. First, we calculated L(Hα) from the reddening-corrected Hα flux. Then the number of ionizing photons needed to produce such luminosities, Nph = 7.3 × 10⁵ L(Hα) photon s⁻¹ (Kennicutt 1998), was estimated and compared with the number of photons emitted by the active nucleus, diluted by the covering factor Ω/4π where Ω is the solid angle of a region as seen from the nucleus. We did not make any hypothesis about the spatial distribution of the gas within each region. By assuming that the nuclear source is an isotropic origin of gas in ENLRs

Figure 18. [S ii] emission-line profiles at different distances from the nucleus. The peaks corresponding to the various components are consistent.

Figure 19. The ionization map with the cone contours overlaid (left), the WFPC2 image of NGC 7212 (middle) and the same with the cone contours overlaid (right).

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emitter of radiation absorbed along the line of sight, we estimated the nuclear ionizing photons by averaging the calculated number of photons ionizing the regions surrounding the nucleus and located within the cones, after having removed the effect of the covering factor. We found $N_{\text{nuc}} = 9.4 \times 10^{53}$ s$^{-1}$. The median value of the ratio between the observed value and the diluted one is 0.84, indicating that the active nucleus is the dominant ionizing source of the regions within the cone.

Estimating the mass of gas can give an idea of the origin of the gas, in fact a large amount of gas can be explained with the acquisition of external material resulting from a merger or an interaction event. The mass of the gas in the ionization cone was estimated following two methods. The first one makes use of the H$\alpha$ luminosity, as explained by Ho (2009):

$$M(L_{\text{H}\alpha}) = 2.97 \times 10^3 \left( \frac{100 \text{ cm}^{-3}}{N_e} \right) \left( \frac{L_{\text{H}\alpha}}{10^{38} \text{ erg s}^{-1}} \right) M_\odot.$$  

The second one assumes a Galactic dust-to-gas ratio and makes use of the interstellar extinction (Fu & Stockton 2007). We used a modified version of their formula:

$$M(A_V) = 1.5 \times 10^7 \text{ kpc}^{-2} \text{ mag}^{-1} A_V (s \times \theta)^2 M_\odot,$$

where $s$ is the scale in kpc arcsec$^{-1}$ and $\theta$ is the size of a region in arcsec. The results of the two methods are different: in particular, the second method gives larger values. The total values are $M(L_{\text{H}\alpha}) = 5.16 \times 10^6 M_\odot$ and $M(A_V) = 3.16 \times 10^8 M_\odot$. The reasons for this discrepancy could be a combination of two effects. First, the $N_e$ value used in equation (2) is generally based on the [S ii]6716/[S ii]6731 ratio, which fails in the case of low electron density. Secondly, the flux of recombination lines depends on electron density squared. Therefore, the first method can cause an underestimate of the ENLR mass, which is likely constituted by a large fraction of low-density gas.

We measured the asymmetry of the [O iii] emission lines by applying the method published by Whittle (1985) to the higher resolution spectra. We calculated the area under the emission line and the wavelengths corresponding to 10 per cent ($\lambda_{10}$), 50 per cent ($\lambda_{50}$) and 90 per cent ($\lambda_{90}$) of the emission-line area. Then we obtained the asymmetry

$$\text{asym} = \frac{a - b}{a + b},$$

where $a = \lambda_{90} - \lambda_{10}$ and $b = \lambda_{50} - \lambda_{50}$. In the case of a blue wing in the line profile the asymmetry is positive, while when a red wing is present the asymmetry is negative. We reconstructed the asymmetry map (Fig. 21), which shows two distinct regions, one with positive (C region in Fig. 21), and the other with negative asymmetry (A region, blue colours in Fig. 21). These two regions match the ionization-cone contours. We found [O iii] emission-line profiles...
with blue wings in the northern part of the ionization cone, while the southern part of the cone is characterized by [O III] with red wings. In the nucleus we found a symmetric profile. This suggests the presence of gas in radial motions, outflow or inflow, inside the cone. The asymmetry does not correspond to the higher FWHM regions, i.e. those orthogonal to the cone, and therefore these high values of FWHM are not an effect of multiple kinematic components.

6 CONCLUSIONS

We have studied the physical and kinematic properties of the circumnuclear gas in the nearby Seyfert 2 galaxy NGC 7212. We analysed this object by means of integral-field and echelle spectra and broad-band images. We pointed out for the first time the presence of an extended ionization cone in NGC 7212, with high values of [O III]/Hβ (up to 12), at a large distance from the nucleus (up to 3.6 kpc). The cone is oriented north-west–south-east at PA = 150°, close to the photometric minor axis of the galaxy, with an opening angle of about 70°. The cone is more extended in the north (7 arcsec = 3.6 kpc) than in the south (5.5 arcsec = 2.8 kpc) direction, while in HST [O III] published images only the southern high-ionization emission was detected, showing a structure made of clouds or filaments. The evidence of dust located in the ENLR also supports the idea that the gas in the cone has a filamentary structure, and suggests that a potential source of error lies in the dereddening, because the way the gas and dust are mixed in and between filaments is in fact unknown. The mass of the ENLR was calculated by means of two different methods based on the Hα luminosity and the interstellar extinction, and it is likely between $5 \times 10^6$ and $3 \times 10^7 M_\odot$. NGC 7212 is in an interacting triplet, with two galaxies in a clear ongoing merger. We found high values of [N II]/Hα and [S II]/Hα towards the interaction region, suggesting a possible combination of ionization by the active nucleus and by shocks. From the 2D velocity maps, we found kinematic decoupling between the stars and gas. The velocity fields are misaligned, with the stellar kinematic minor axis aligned with the photometric minor axis while the gas kinematic axis is tilted 30° with respect to the stellar one. We studied the asymmetry of the emission-line profiles inside the ionization cone and we found [O III] with blue wings in the northern side of the cone, while the southern side of the cone is characterized by [O III] with red wings. In the nucleus the profiles are symmetric. This suggests the presence of gas in radial motion, which is confirmed also by the analysis of high-resolution spectra. In fact, studying the echelle data, we found that the ionized gas is characterized by multiple kinematic components at different velocities. We found at least four components: at ~300, ~150, 170 and 450 km s$^{-1}$ with respect to the recession velocity. The ENLR gas metallicity was estimated by measuring the observed emission-line ratios and comparing them with CLOUDY models, obtaining indications of subsolar values. All these properties support the idea of an external origin for the ENLR gas in NGC 7212, likely due to gravitational interaction effects in action in this triple system.

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