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A multiwavelength study of a massive, active galaxy at $z \sim 2$: coupling the kinematics of the ionized and molecular gas

Federica Loiacono [1,2]★ Margherita Talia [1,2] Filippo Fraternali,[1,3] Andrea Cimatti,[1,4] Enrico M. Di Teodoro [5] and Gabriel B. Caminha[3]

[1]*Dipartimento di Fisica e Astronomia, Università di Bologna, via Gobetti 93/2, I-40129 Bologna, Italy*
[2]*INAF-Osservatorio di Astrofisica e Scienza dello Spazio, via Gobetti 93/3, I-40129 Bologna, Italy*
[3]*Kapteyn Astronomical Institute, University of Groningen, Postbus 800, NL-9700 AV Groningen, the Netherlands*
[4]*INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy*
[5]*Research School of Astronomy and Astrophysics, The Australian National University, Canberra, ACT 2611, Australia*

ABSTRACT

We report a multiwavelength study of the massive ($M_\star \gtrsim 10^{11} M_\odot$), $z \sim 2$ star-forming galaxy GMASS 0953, which hosts an obscured AGN. We combined near-infrared observations of the GNIRS, SINFONI and KMOS spectrographs to study the kinematics of the [O III] $\lambda 5007$ and Hα emission lines. Our analysis shows that GMASS 0953 may host an ionized disc extending up to 13 kpc, which rotates at a velocity of $V_{ion} = 203^{+17}_{-20}$ km s^{-1} at the outermost radius. Evidence of rotation on a smaller scale ($R \sim 1$ kpc) arises from the CO(J = 6–5) line. The central velocity $V_{CO} = 320^{+92}_{-53}$ km s^{-1} traced by the molecular gas is higher than V_{ion}, suggesting that the galaxy harbours a multiphase disc with a rotation curve that peaks in the very central regions. The galaxy appears well located on the $z = 0$ baryonic Tully–Fisher relation. We also discuss the possibility that the [O III] $\lambda 5007$ and Hα velocity gradients are due to a galactic-scale wind. Besides, we found evidence of an AGN-driven outflow traced by a broad blueshifted wing affecting the [O III] $\lambda 5007$ line, which presents a velocity offset $\Delta v = -535 \pm 152$ km s^{-1} from the systemic velocity. Because of the short depletion time-scale ($\tau_{dep} \sim 10^8$ yr) due to gas ejection and gas consumption by star formation activity, GMASS 0953 may likely evolve into a passive galaxy. However, the role of the AGN in depleting the gas reservoir of the galaxy is quite unclear because of the uncertainties affecting the outflow rate.

Key words: galaxies: active – galaxies: evolution – galaxies: high-redshift – galaxies: kinematics and dynamics.

1 INTRODUCTION

In the last years significant progress has been made in the study of $z \sim 2$ massive ($M_\star \gtrsim 10^{11}$ M$_\odot$) galaxies. Investigating these systems is pivotal to shed light on the mechanisms that regulate the mass assembly at the peak epoch of both star formation and nuclear activity (e.g. Madau & Dickinson 2014). Near-infrared (NIR) observations using integral field spectroscopy have revealed that rotating discs are common in these objects (Förster Schreiber et al. 2009; Wisnioski et al. 2015), with important implications for their growth mode. The interplay between active galactic nuclei (AGNs) and their hosts have been deeply investigated through spatially resolved observations of ionized outflows traced by strong emission lines (e.g. Harrison et al. 2012; Genzel et al. 2014; Carniani et al.

2015) while at the submillimetre wavelengths interferometers as the NOrthern Extended Millimeter Array (NOEMA) and the Atacama Large Millimeter Array (ALMA) have provided key information on the molecular gas content of massive systems through CO lines and dust emission (e.g. Scoville et al. 2016; Tacconi et al. 2018).

Nevertheless, a number of questions remain open. A first issue concerns the so-called 'quenching' of star formation in massive spheroids. Several studies show that massive spheroidal galaxies are dominated by old stellar populations already at $1 < z < 2$ (e.g. Cimatti et al. 2004, 2008; Glazebrook et al. 2004; Onodera et al. 2015). Because of their size, considerably smaller compared to present-day ellipticals, and high stellar density the progenitors of these systems are thought to be compact star-forming galaxies (SFGs) at $1.5 < z < 3$ (e.g. van Dokkum et al. 2015). These objects are often characterized by a short depletion time-scale inferred from the molecular gas content (Spilker et al. 2016; Barro et al. 2017; Tadaki et al. 2017) suggesting that they are rapidly exhausting

★ E-mail: federica.loiacono2@unibo.it

Table 1. Main properties of GMASS 0953.

RA (J2000) (1)	Dec. (J2000) (2)	z (3)	$R_{\mathrm{eff},H\,\mathrm{band}}$ (kpc) (4)	$M_\star$ ($10^{11}M_\odot$) (5)	$\mathrm{SFR_{IR}}$ ($M_\odot\,\mathrm{yr^{-1}}$) (6)	$\mathrm{SFR_{H\alpha}}$ ($M_\odot\,\mathrm{yr^{-1}}$) (7)	L_X(2–10 keV) (erg s^{-1}) (8)	HR (9)	N_{H} (10^{24} cm^{-2}) (10)	$E(B-V)$ (11)	n_{e} (cm^{-3}) (12)
3:32:31.4	-27:46:23.2	2.226	2.5	1.15 ± 0.10	214 ± 20	498 ± 33	5×10^{44}	0.6	$4.4^{+4.7}_{-1.7}$	0.8 ± 0.3	$\sim$500

Note. Column description: (1), (2) sky-coordinates of GMASS 0953 in the *HST*/WFC3 *H*-band image. (3) Redshift derived from the [O III] λ5007 narrow line. (4) Effective radius measured on the *HST*/WFC3 *H*-band image (van der Wel et al. 2014). (5) Stellar mass derived from SED fitting. (6), (7) Star formation rate derived from the infrared luminosity and from Hα. (8) X-ray intrinsic luminosity (Dalla Mura et al., in preparation). (9) Hardness ratio (Luo et al. 2017). (10) Column density (Dalla Mura et al., in preparation). (11) Colour excess derived from the Hα and Hβ line ratio. (12) Electron number density evaluated from the [S II] λλ6716, 6731 line ratio.

their internal reservoir for star formation. However, new gas can be accreted from the circumgalactic and intergalactic medium (CGM/IGM) as shown by numerical simulations (Kereš et al. 2005; Dekel et al. 2009), which may keep sustaining the star formation activity. To explain the quenching of star formation in spheroidal galaxies is thus necessary a mechanism that removes or heats the accreted gas, in order to make it not available to form stars. AGNs could be crucial in this context through feedback mechanism (see Fabian 2012 for a review). In particular, high-velocity winds ($v > 500$ km s^{-1}) extending on kpc-scale driven by the AGN may be efficient in depleting the galaxy of the accreted gas, cutting off the fuel for star formation. This ejective feedback is implemented in models as a way to prevent both black hole and galaxy growth (e.g. Di Matteo, Springel & Hernquist 2005; King 2005; Springel, Di Matteo & Hernquist 2005; Hopkins et al. 2016; Weinberger et al. 2017; Nelson et al. 2018). However, if on the theoretical side AGN feedback is commonly invoked to explain the observed properties of galaxies, from the observational point of view we still lack a robust understanding of how AGNs shape their hosts (Cresci & Maiolino 2018).

An important clue about the influence of AGN feedback in turning massive SFGs to passive spheroids may arise from the population of the red sequence in the colour–mass plane (Cassata et al. 2008) by spheroidal galaxies between $z \sim 2.4$ and $z \sim 1.4$ and the decrease of AGN activity in SFGs between the same redshifts (Cimatti et al. 2013). Rest-frame UV, stacked spectra of active galaxies in the sample of Cimatti et al. (2013) show absorption lines with average velocity offset $\Delta v \gtrsim -500$ km s^{-1} that are signatures of gas outflows, highlighting that the progenitors of passive spheroids may be found among the SFGs with AGN feedback in action. However, the picture is still hazy and detailed observations of systems hosting AGN-driven outflows are needed especially at $z \gtrsim 2$, i.e. the formation epoch of the spheroids progenitors, in order to assess the efficiency of AGN winds in suppressing star formation.

Another key issue concerning $z \sim 2$ massive galaxies relates to the kinematics of the interstellar medium (ISM). Using rotation curves to investigate the kinematics of $z \sim 2$ discs provides important constraints on the dark matter content and on the evolution of scaling relations such as the Tully–Fisher (Tully & Fisher 1977) whose matching is an important test bench for theoretical models (e.g. Ferrero et al. 2017). Most of the studies at $z \sim 2$ uses the ionized phase of the ISM to trace the kinematics of massive galaxies, which has been deeply investigated through large programs such as SINS (Förster Schreiber et al. 2009) and KMOS^{3D} (Wisnioski et al. 2015). The ionized gas has though the drawback to be more affected compared to the cold gas by non-circular motions (e.g. outflows), which may make this tracer, if considered alone, not representative of the overall kinematics (e.g. Lelli et al. 2018). A multiwavelength approach that employs different ISM tracers (e.g.

molecular, ionized) is hence required in order to build a robust picture of the kinematics of $z \sim 2$ objects. At the moment this kind of studies is rare, regarding just a scanty number of high-z galaxies (see e.g. Genzel et al. 2013; Chen et al. 2017; Lelli et al. 2018; Übler et al. 2018; Herrera-Camus et al. 2019) because of the lack of multiwavelength spectroscopic data at high redshift.

Here we report a multiwavelength study of the $z \simeq 2.226$ galaxy GMASS 0953. This is a massive, compact SFG, which hosts an obscured AGN. This source has been already studied by Talia et al. (2018), who investigated its molecular content revealing the existence of a rotating disc traced by the CO(J = 6–5) line. Moreover, Popping et al. (2017) found a very short depletion time-scale for the molecular gas, which implies that the galaxy is rapidly consuming its gas reservoir and it will likely evolve into a passive system. This work integrates the aforementioned picture adding information on the ionized gas kinematics. In particular, we discuss how the ionized gas motions relate to the molecular phase and what is the effect of the AGN feedback on the galaxy. In our analysis, we used NIR observations of [O III] λ5007 and Hα combining a slit spectrum, obtained with the Gemini Near InfraRed Spectrograph (GNIRS), with integral field data collected by the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) and the *K*-band Multi-Object Spectrograph (KMOS). The use of different instruments that work at similar wavelengths has the advantage to corroborate the results arising from independent measurements and provides also complementary details (see Section 3). The paper is organized as follows: in Section 2 we describe the main properties of GMASS 0953 while Section 3 concerns the data analysis. The multiwavelength kinematics is discussed in Section 4 and Section 5, while we study the AGN feedback in Section 6. We finally summarize the obtained results in Section 7. We adopt a ΛCDM cosmology with $\Omega_\Lambda = 0.71$, $\Omega_M = 0.29$, and $H_0 = 69.6$ km s^{-1} Mpc^{-1}. In this cosmology 1 arcsec corresponds to 8.4 kpc at $z \simeq 2.226$. We assume a Chabrier (2003) IMF.

2 GMASS 0953: A GLOBAL PORTRAIT

GMASS 0953 (also known as K20-ID5, GS3-19791, 3D-*HST* GS30274, e.g. Daddi et al. 2004; Popping et al. 2017; Wisnioski et al. 2018) is a massive SFG at $z \simeq 2.226$ located in the Chandra Deep Field South (CDFS; Giacconi et al. 2002) (see Table 1 for the main properties of the galaxy). It presents an irregular morphology (Fig. 1), visible in both the *HST*/WFC3 (*H* band, 1.5 μm) and *HST*/ACS (*z* band, 0.85 μm) images, which appears bright and compact in the central region ($R_{\mathrm{eff},H\,\mathrm{band}} \sim 2.5$ kpc, corresponding to 0.3 arcsec; van der Wel et al. 2014), showing also an off-nuclear emission to the west, interpreted as an asymmetric stellar disc or a merger remnant (van Dokkum et al. 2015; Wisnioski et al. 2018).

Figure 1. *H*-band (1.6 μm, upper panel) and *z*-band (0.85 μm, bottom panel) images of GMASS 0953 (*HST*/WFC3 and ACS). The lowest contour is at 5σ. The blue crosses show the emission peak, which we take as the photometric and dynamical centre of the galaxy. The central region appears extremely bright and compact with an effective radius $R_e \sim 2.5$ kpc, estimated from the *H*-band image (van der Wel et al. 2014). The dashed line indicates the major axis (position angle $\phi = 94°$).

The galaxy was selected among the AGN-hosts of Cimatti et al. (2013), which represent a subsample of the GMASS survey (Kurk et al. 2013), including active galaxies with a stellar mass $M_\star > 10^{10}$ $M_\odot$ and a X-ray luminosity $L_X > 10^{42.3}$ erg s^{-1}. The AGN activity of GMASS 0953 was inferred from the X-ray luminosity $L_X \sim 5 \times 10^{44}$ erg s^{-1} corrected for obscuration (Dalla Mura et al., in preparation) and the hardness ratio[1] HR = 0.6 (Luo et al. 2017), both higher than those measured in purely star-forming systems (Norman et al. 2004). The optical emission-line ratios are also consistent with an AGN (Newman et al. 2014) even if shock ionization by a strong galactic wind is also possible (van Dokkum et al. 2005). Indications of outflowing material, likely boosted by the AGN, were observed in the rest-frame optical spectrum (Förster Schreiber et al. 2014; Genzel et al. 2014), in the UV absorption lines (Cimatti et al. 2013) and we found further evidence in this work. On the other hand, the AGN activity does not emerge from the UV emission lines. This was verified by the measurement of the line ratios of C IV λ1550, He II λ1640, and C III] λ1909 using MUSE data (P. Rosati, private communication). These ratios place GMASS 0953 closer to the observed SFGs than to the AGNs in the diagnostic diagram of Feltre, Charlot & Gutkin (2016), likely because of the high obscuration ($N_H = 4.4^{+4.7}_{-1.7} \times 10^{24}$ cm^{-2}, Dalla Mura et al., in preparation).

Thanks to the available photometric spectral energy distribution (SED)[2] from the UV to submm wavelengths, we estimated several properties of the galaxy. The stellar mass $M_\star = (1.15 \pm 0.10) \times 10^{11}$

[1]The hardness ratio is defined as HR = (H − S)/(H + S) where H and S are the photon counts in the hard (2–10 keV) and soft (0.5–2 keV) X-ray band, respectively.

[2]The photometric SED of GMASS 0953 was obtained collecting data from MUSIC (Grazian et al. 2006), SPITZER/MIPS (Magnelli et al. 2011),

$M_\odot$ was evaluated from the SED decomposition applying a modified MAGPHYS code (da Cunha, Charlot & Elbaz 2008) that includes the AGN component, relevant in the mid-infrared (Berta et al. 2013), as done by Delvecchio et al. (2014). The derived infrared luminosity L_{IR} in the rest-frame 8–1000 μm, corrected for the AGN contribution, was used to estimate the star formation rate SFR$_{IR}$ = 214 ± 20 $M_\odot$ yr^{-1} through the Kennicutt (1998) relation, rescaled to a Chabrier (2003) IMF. The stellar mass and the SFR place GMASS 0953 on the main sequence at $z \sim 2$ (e.g. Daddi et al. 2007).

The kinematical properties of GMASS 0953 were investigated by Förster Schreiber et al. (2009), who inferred an upper limit for the dynamical mass $M_{dyn} < 5.8 \times 10^{11}$ $M_\odot$. Wisnioski et al. (2018) modelled the Hα kinematics revealing a disc structure extending up to 13 kpc with an average rotation velocity of 200 km s^{-1}. Evidence of rotation on a smaller scale was found by Talia et al. (2018) studying the CO (J = 6-5) transition produced by a rapidly rotating ($V_{CO} = 320^{+92}_{-53}$ km s^{-1}) and very compact core ($R_{CO} = 0.75 \pm 0.25$ kpc). Talia et al. (2018) found also a short depletion time-scale for the molecular gas ($\tau_{dep} < 150$ Myr) and a low molecular gas fraction ($f_g < 0.2$) in agreement with Popping et al. (2017), which imply that GMASS 0953 might quickly cease its star formation activity, likely turning into a passive galaxy.

3 DATA ANALYSIS

In the sections below we describe the spectroscopic data set and the line fitting methods that we used to evaluate the physical properties of GMASS 0953. We also discuss the derivation of total flux maps from the integral field data, which show the spatially resolved emission-line morphology. We focus in particular on the [O III] λ5007 and Hα lines that are then used to model the kinematics (see Section 4)

3.1 GNIRS one-dimensional spectrum

We used the data of Kriek et al. (2008; see van Dokkum et al. 2005 for the details) obtained with the GNIRS spectrograph (Elias et al. 2006) at the Gemini South Observatory. They consist of a one-dimensional and two-dimensional spectra, publicly available, that cover the range 1.0–2.5 μm with a resolving power ~ 1800. Several emission lines are present such as [O II] λλ3727, 3729, [O III] λλ4959, 5007, Hα, Hβ, [N II] λλ6548, 6584, and the [S II] λλ6716, 6731 doublet (Fig. 2, top panel).

We analysed the one-dimensional spectrum through line fitting. The analysis was carried out with SPECFIT (Kriss 1994), a spectral fitting tool that runs in the Image Reduction and Analysis Facility (IRAF) environment. The galaxy emission was modelled with a linear continuum and eight Gaussian components, one for each line. We divided the spectrum into two ranges including Hβ, [O III] λλ4959, 5007 (1.5–1.7μm) and Hα, [N II] λλ6548, 6584, [S II] λλ6716, 6731 (2.0–2.3 μm) on which we performed two fits separately. The ratio between the line centroids of oxygen, nitrogen, and sulphur doublets was fixed to the theoretical one (0.990, 0.995, and 0.998, respectively). We initially used two Gaussian functions to reproduce [O III] λλ4959, 5007. However, both the lines show a broad, blueshifted wing, detected at 3σ and 5σ of significance for [O III] λ4959 and [O III] λ5007, that is not reproduced by one Gaussian. In order to account for these emissions, we performed a

Herschel/PACS (Magnelli et al. 2013), SPIRE (Roseboom et al. 2010), and ALMA (Popping et al. 2017; Talia et al. 2018; Ueda et al. 2018).

Figure 2. Top panel: GNIRS one-dimensional spectrum. Middle panel: line fits of H β and [O III] $\lambda\lambda4959$, 5007. Bottom panels: line fits of [N II] $\lambda\lambda6548,6584$ and H α (left) and [S II] $\lambda\lambda6716,6731$ (right, fit (b) of Table 2). The black line represents the model superimposed on the data (blue line), with the single components in red. The vertical bands show the location of the atmospheric lines. The profile of [O III] $\lambda\lambda4959$, 5007 shows a blueshifted wing that was modelled with a broad Gaussian function (FWHM $\sim$ 1270 km s^{-1}).

second fit adding two other Gaussians (Fig. 2, middle panel). This addition improved significantly the reduced chi-square χ^2_{dof} from 1.23 to 1.01. The new fitted components have a full width at half maximum FWHM $\sim$ 1270 km s^{-1}, much broader in comparison to those already fitted (FWHM $\sim$ 370 km s^{-1}). The blueshifted component of [O III] λ5007 is also clearly visible in the GNIRS two-dimensional spectrum (broad component in Fig. 5, left-hand panel).

In the case of H α and [N II] $\lambda\lambda$6548, 6584 we note that the fitted line widths result considerably larger than the FWHM of the [O III] $\lambda\lambda$4959, 5007 narrow components and the [S II] $\lambda\lambda$6716, 6731 lines (Table 2). This could be due either to the overlapping of several sky lines, which may alter the line profiles, or to the presence of blueshifted components, hidden by the line blending, that were not modelled separately (Fig. 2, bottom left panel). The latter interpretation could be supported by the blueshifted emission affecting the H α profile after the subtraction of the [N II] $\lambda\lambda$6548, 6584 models from the KMOS data cube (see Section 3.3 and Fig. 5, right-hand panel).

In the [S II] $\lambda\lambda$6716, 6731 case, two fits have been performed. If only the centroids ratio is fixed, the FWHM of [S II] λ6731 results indeed higher than the one relative to [S II] λ6716 (Table 2, fit (a)). However, the [S II] λ6731 emission is affected by a sky line (Fig. 2, bottom right panel) that likely alters its profile. In order to account for this uncertainty, we performed a second fit in which the line widths were matched to the FWHM of [S II] λ6716 (i.e. the more reliable one) calculated in the first fit.

All the parameters derived from line fitting are reported in Table 2. The fitted values are consistent with the ones found by van Dokkum et al. (2005) despite of the addition of the broad [O III] $\lambda\lambda$4959, 5007 components.

We used the fitted quantities to evaluate some global properties of GMASS 0953 like dust obscuration, the SFR and the electron number density. Assuming a Calzetti et al. (2000) extinction curve, we estimated the colour excess $E(B - V) = 0.8 \pm 0.3$ from the line ratio of H α and H β. This value indicates that GMASS 0953 is a highly obscured system (see also van Dokkum et al. 2005). Before calculating the colour excess, the fluxes of H α and H β were corrected for the stellar continuum absorption considering an equivalent width EW = 4 $\pm$ 1 Å (van Dokkum et al. 2005). Then we derived the SFR$_{H\alpha}$ = 498 $\pm$ 33 M$_\odot$ yr^{-1} using the de-reddened H α through the Kennicutt (1998) relation, rescaled to a Chabrier (2003) IMF. This value is higher than the one obtained using the infrared luminosity, likely because of the AGN contamination (see also Section 3.3).

Finally, we measured the electron number density n_e from the [S II] $\lambda\lambda$6716, 6731 line ratio calculated in the two fits. Both ratios are compatible with an electron number density of 500 cm^{-3} (Osterbrock & Ferland 2006), which can vary in the range 100 $< n_e$ [cm^{-3}] $< 2 \times 10^3$ because of the uncertainties in the line ratios. Values of $n_e \sim 500$ cm^{-3} are typical of AGNs narrow-line regions. However, it is highly reasonable that the galaxy ISM also contributes to it because of the large size of the ionized gas, which extends over the entire galaxy as visible from the SINFONI and KMOS maps (Figs 3 and 9).

3.2 SINFONI integral field spectrum

We analysed the data of GMASS 0953 from the SINS survey (see Förster Schreiber et al. 2009 for the observation details and data reduction) carried out with the SINFONI (Eisenhauer et al. 2003) integral field spectrograph (IFS) at the ESO Very Large Telescope

(VLT). They consist in a data cube covering the *H* band (1.5–1.7 μμm) with a resolving power $\sim$ 2900 and a channel width of 1.95 Å containing the sky-subtracted data. The visible lines are H β and the [O III] $\lambda\lambda$4959, 5007 doublet. The observation is seeing limited with a PSF of 0.7 arcsec. We verified the SINFONI astrometry in order to properly overlap the emission-line maps on the *HST* images of GMASS 0953 as explained in Appendix A.

The SINFONI data cube (and also the KMOS one) was handled using the software GIPSY (van der Hulst et al. 1992). We focused in particular on the [O III] λ5007 narrow line fitted in the GNIRS spectrum, which we used for the kinematic modelling due to its high brightness, and on the [O III] λ5007 blueshifted component. The total flux map, which shows the [O III] λ5007 narrow-line morphology, was derived co-adding $N = 17$ channels after masking out all the pixels with a signal-to-noise ratio $F/\sigma < 1$ and removing by hand (channel by channel) the instrumental noise peaks present in the field of view. We considered as the typical noise in one channel the average standard deviation $\sigma = 1.7 \times 10^{-20}$ erg s^{-1} cm^{-2} Å^{-1} of the signal in the channels without emission from the galaxy. The noise of the [O III] λ5007 map was estimated by the relation $\sigma_{TOT} = \sigma\sqrt{\bar{N}}$, where $\bar{N} = 9$ is the average number of co-added channels at each pixel position in the map. Due to the masking process, the number of co-added channels is not constant for all the pixels.

From the map[3] (Fig. 3, top left panel), the [O III] λ5007 narrow-line emission appears quite extended (see Fig. 9 for a visual comparison with the *HST/WFC3* image). Moreover, the flux distribution is very asymmetric, with the western side much brighter than the eastern one. The asymmetry in the flux distribution is visible also in the GNIRS two-dimensional spectrum (narrow component in Fig. 5, left-hand panel).

Then, after a by eye inspection of the whole data cube, we stacked the channels without emission lines or sky subtraction residuals to obtain the continuum radiated by the galaxy. The continuum emission is produced by the inner region of GMASS 0953 (Fig. 3, top left panel) and it originates from the stellar component; however, also a contribution from the obscured AGN is possible. This is indeed less affected by dust extinction at rest-frame optical wavelengths than in the UV, where the nuclear activity of GMASS 0953 does not emerge (see Section 2). In order to properly overlap the SINFONI line maps to the *HST* images of the galaxy (see Appendix A), we evaluated the coordinates of the continuum peak fitting the stacked emission with a two-dimensional elliptical Gaussian. We observe that there is a shift of 0.58 $\pm$ 0.24 arcsec (equivalent to 4.9 $\pm$ 2.0 kpc) between the fitted coordinates and the [O III] λ5007 narrow-line peak (cross in Fig. 3, top left panel), evaluated also through a two-dimensional Gaussian fit.

The detection of blueshifted emission with respect to the [O III] λ5007 narrow line, corresponding to the broad component fitted in the GNIRS spectrum (Fig. 2, middle panel), was confirmed by the SINFONI data, which also provided its spatial position. Adding $N = 18$ channels from 4974 to 4995 Å (rest-frame wavelengths), we obtained a 6σ detection localized near the galaxy centre (Fig. 3, top right panel). In order to assess if this emission was truly due to [O III] λ5007 and not to the stellar continuum, which also peaks near the galaxy centre, we compared it to the continuum flux of $N = 18$ co-added channels, i.e. the same number of stacked channels for the [O III] λ5007 broad component. These channels

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[3]We point out that the [O III] λ5007 map was not continuum subtracted because the contributed continuum flux on $N = 17$ channels is very low (less of 2σ significance).

Table 2. Emission-line properties derived from the line fitting of the GNIRS spectrum.

Line	Flux (10^{-19} erg s^{-1} cm^{-2})	Line centroid (rest frame, Å)	FWHM (km s^{-1})
Hβ	278 ± 58	4862.4 ± 0.4	264 ± 63
[O III]$\lambda 4959$ (narrow)	936 ± 125	4958.7 ± 0.2	394 ± 40
[O III] $\lambda 4959$ (broad)	501 ± 157	4949 ± 2	1170 ± 389
[O III] $\lambda 5007$ (narrow)	2084 ± 249	5006.8 ± 0.2	354 ± 31
[O III] $\lambda 5007$ (broad)	1099 ± 262	4998 ± 2	1376 ± 356
[N II] $\lambda 6548$	847 ± 107	6547.4 ± 0.5	756 ± 78
Hα	2312 ± 108	6562.6 ± 0.3	604 ± 30
[N II] $\lambda 6584$	2120 ± 149	6583.7 ± 0.5	756 ± 78
[S II] $\lambda 6716$ (a)	307 ± 58	6715.9 ± 0.6	319 ± 79
[S II] $\lambda 6731$	327 ± 73	6731.4 ± 0.6	413 ± 92
[S II] $\lambda 6716$ (b)	307 ± 58	6716.0 ± 0.5	319 ± 79
[S II] $\lambda 6731$	282 ± 59	6731.5 ± 0.5	319 ± 79

Note. Letter (a) refers to the line fit of the [S II] $\lambda\lambda 6716$, 6731 doublet in which only the centroids ratio was fixed to the theoretical value while letter (b) indicates the fit in which the FWHM of [S II] $\lambda 6731$ was matched to the FWHM of [S II] $\lambda 6716$ calculated in fit (a).

Figure 3. Emission-line maps extracted from the SINFONI and KMOS data cubes. Top panels: narrow and broad component of [O III] $\lambda 5007$ (black contours and colours). Flux contour levels are at 3σ, 6σ, 12σ and 24σ for the [O III] $\lambda 5007$ narrow line and at 2σ, 4σ and 6σ for the [O III] $\lambda 5007$ broad component. The red contour shows the continuum emission stacked on the entire spectrum (left-hand panel) and on $N = 18$ channels (right-hand panel), i.e. the same number of co-added channels for the [O III] $\lambda 5007$ blueshifted component. Compared to the centre of GMASS 0953 (0 arcsec offset in the map) the [O III] $\lambda 5007$ narrow-line morphology appears asymmetric, concentred in the western region of the galaxy, as indicated also by the off-centred emission peak (orange cross); on the other hand the [O III] $\lambda 5007$ blueshifted line emits close to the nuclear region. Bottom panel: Hα emission. Flux contour levels are at 3σ, 6σ, 12σ, 24σ and 48σ. Compared to the [O III] $\lambda 5007$ emission Hα shows a more symmetric morphology, with the emission peak (orange cross) close to the centre. All the maps are centred on the peak of the *HST/H*-band image. The beam size of SINFONI and KMOS is shown in pink.

Figure 4. Hα and [N II] $\lambda\lambda$6548, 6584 emission lines (KMOS data). Left-hand panel: line fit of Hα and [N II] $\lambda\lambda$6548, 6584 superimposed on the data (black line) in one pixel. The fitted Gaussians are shown in coloured lines with the total model in red. The purple line indicates the continuum level while the noise spectrum is shown in brown. Right-hand panel: total Hα emission (orange) after the subtraction of [N II] $\lambda\lambda$6548, 6584 and stellar continuum. See also Appendix B.

were selected at wavelengths close to the oxygen line. As evident from the comparison of the contours, the blueshifted component is significantly brighter than the continuum, hence it traces a genuine emission from the [O III] λ5007 line.[4] This component is clearly visible also by looking at the position-velocity (pv) diagram extracted one pixel above the major axis of the galaxy (Fig. 5, middle panel). It appears like an evident off-set emission from the [O III] λ5007 narrow line reaching a velocity difference from the bulk of the galaxy emission of ~ -1200 km s^{-1}.

3.3 KMOS integral field spectrum

To model the Hα kinematics, we employed integral field data from the KMOS^{3D} survey (Wisnioski et al. 2015), which investigates the kinematics of galaxies at $0.7 < z < 2.7$ using the NIR spectrograph KMOS (Sharples et al. 2013) at the VLT. GMASS 0953 is one of the compact, massive galaxies in the sample of Wisnioski et al. (2018). It was observed with a resolving power $\sim$3965 at Hα wavelengths and a spatial resolution of 0.59 arcsec. The spectrum covers the range 1.95–2.3 μm with a channel width of 2.8 Å and an average noise of 1.6×10^{-20} erg s^{-1}cm^{-2} Å^{-1} in each channel. The visible lines are Hα, [N II] $\lambda\lambda$6548, 6584 and the [S II] $\lambda\lambda$6716, 6731 doublet. For the observation details and the data reduction see Wisnioski et al. (2015).

In order to study the kinematics of Hα, we carried out a line fit to subtract the stellar continuum and the nitrogen emission that is partially mixed with the Hα line (Fig. 4, left-hand panel), as already seen in the GNIRS spectrum (Fig. 2, bottom left panel). For details about the line fit, which we performed pixel by pixel, see Appendix B. After subtracting the [N II] $\lambda\lambda$6548, 6584 models from the original spectrum, a new data cube containing only the Hα emission was built (Fig. 4, right-hand panel). We then stacked the channels with the line ($N = 25$) to obtain the total flux map (Fig. 3, bottom panel). In comparison to the [O III] λ5007 emission, the Hα morphology appears much less asymmetric, with the line peak closer to the galaxy centre. The central position of the peak

may support the substantial contribution to the line from the AGN, which explains the discrepancy between the Hα derived SFR and the one inferred from the IR luminosity (see Section 3.1).

4 KINEMATIC MODELLING

The SINFONI and KMOS data were used to perform a study of the kinematics of the [O III] λ5007 narrow line and Hα. The two lines show a large-scale velocity gradient that we analysed in details (Fig. 5). In particular, we worked under the hypothesis that the observed velocity gradients are due to gas rotation and we modelled the line emission as if it were produced by a rotating disc. In Section 4.3 we also discuss an alternative interpretation of the velocity gradient.

4.1 Signatures of an ionized disc

As suggested by an inspection of the GNIRS two-dimensional spectrum (Fig. 5, left-hand panel), the [O III] λ5007 narrow-line emission appears tilted along the slit, showing a large-scale velocity gradient that could be due to gas rotation. The emission extends over $\sim$3 arcsec, corresponding to 25 kpc. This large-scale gradient has been confirmed by the pv diagram of [O III] λ5007 extracted roughly along the major axis of GMASS 0953 (see Fig. 1, top panel) using the SINFONI data (middle panel in Fig. 5). Before the extraction, the data cube channel separation was converted into velocity after determining $\lambda_{\rm rest} = (\lambda_{50}^{B} + \lambda_{50}^{R})/2$, i.e. the average value between the wavelengths λ_{50} where the flux of the global [O III] λ5007 profile is 50 per cent of the peak, with 'B' and 'R' that refer to the blue and red side of the line profile, respectively. This quantity was set to zero for simplicity and allowed us to fix the channel velocity spacing to $\Delta v = 36.6$ km s^{-1} at the [O III] λ5007 wavelengths.[5]

The emission of the [O III] λ5007 narrow line covers about 500 km s^{-1} with the western, bright side of the galaxy moving in our direction while the eastern, dimmer part is globally redshifted.

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[4]In the [O III] λ4959 case an emission near the galaxy centre was also detected but it was only slightly brighter than the continuum level so we do not report it.

[5]For Hα the channel velocity spacing is 39.8 km s^{-1}. The $\lambda_{\rm rest}$ value was used also to convert the wavelengths of the GNIRS two-dimensional spectrum into velocity.

Figure 5. Position-velocity (pv) diagrams of [O III] λ5007 and H α roughly along the major axis of GMASS 0953 extracted from the GNIRS two-dimensional spectrum (left), SINFONI (middle), and KMOS (right) data cubes. Flux contour levels are at $\pm 2\sigma$, $\pm 4\sigma$, 8σ and 16σ. Both the [O III] λ5007 and H α lines present a large-scale velocity gradient that extends up to 500 km s^{-1} at the external radii and goes far beyond in the central region. However, in the H α case, a contamination from the [N II] λλ6548, 6584 residuals is possible. The central excess up to ~ -1200 km s^{-1} presented by [O III] λ5007 in both the GNIRS and SINFONI pv diagrams corresponds to the broad blueshifted component fitted in the GNIRS one-dimensional spectrum.

Because of an atmospheric line, it is not clear if the galaxy emission reaches velocity higher than -300 km s^{-1}, which would be hidden by the sky subtraction. The large-scale gradient extracted from the SINFONI data is consistent with the observed velocity in the GNIRS two-dimensional spectrum, even if the latter shows a slightly higher velocity for the receding half probably because of the better sensitivity and lower spectral resolution.

As we noted in Section 3.2, in the central region of GMASS 0953 the [O III] λ5007 gradient extends up to ~ -1200 km s^{-1} (broad component in Fig. 5, middle panel). The interpretation of this blueshifted emission, which is not due to gas rotation, will be discussed in Section 6.

Interestingly, a large-scale velocity gradient is also shown by H α (Fig. 5, right-hand panel). The line shows a slightly asymmetric morphology, not marked as in the [O III] λ5007 case, with the redshifted half more clearly visible. The emission from the external regions shows the same velocity gradient of the [O III] λ5007 line for both sides while, in the inner part, it extends up to 500 km s^{-1} for the red half and goes far beyond on the blue side. This blueshifted emission, which extends on a smaller scale (~ 0.8 arcsec, corresponding to ~ 6.7 kpc) with a velocity up to -700 km s^{-1}, highlights the presence of a possible blueshifted component also in H α, though we point out a probable contamination from the residuals of the [N II] λ6548 subtraction. Evidence of a blueshifted component necessary to reproduce H α and the [N II] λλ6548, 6584 doublet was found by Förster Schreiber et al. (2014) and Genzel

et al. (2014), who interpreted it as a nuclear outflow linked to the AGN activity of the galaxy.

A velocity gradient, extending in the same direction of the [O III] λ5007 and H α large-scale observed gradients, is also shown by the CO(J = 6–5) line, which traces a high-density, compact molecular disc hosted by GMASS 0953 (Talia et al. 2018). This fact suggests that the galaxy harbours a multiphase disc that includes both an ionized and a molecular component (see Section 5).

4.2 Three-dimensional disc modelling

We interpreted both the [O III] λ5007 and H α large-scale velocity gradient as due to a rotating disc that we modelled with the publicly available software ^{3D}BAROLO (Di Teodoro & Fraternali 2015). This is an algorithm based on the tilted-ring model (Rogstad, Lockhart & Wright 1974) that derives rotation curves through a three-dimensional modelling of data cubes. In this approach, the rotation velocity and the velocity dispersion are computed directly comparing the observed data cube with an artificial one that simulates an IFS observation, avoiding the extraction of the two-dimensional velocity field. The latter is indeed affected by beam smearing (Begeman 1987), a problem due to the low spatial resolution (e.g. atmospheric seeing) that spreads the line emission within a region on the adjacent ones. The result is that the observed velocity gradients are artificially flattened with a consequent increase of the line broadening, which makes the

Figure 6. Position-velocity diagrams of the [O III] λ5007 narrow line (top panel) and Hα (bottom panel) extracted along the major axis ($\phi = 94°$) of GMASS 0953. Blue contour and colours refer to the data while the ^{3D}BAROLO disc model is marked in red. Flux contour levels are at $\pm2\sigma$, 4σ, 8σ, 16σ and 32σ. The yellow dots show the rotation curve projected along the line of sight.

kinematical parameters derived from the two-dimensional velocity field less reliable (see Di Teodoro & Fraternali 2015 and Di Teodoro, Fraternali & Miller 2016 for more details). On the other hand, a three-dimensional modelling is not affected by beam smearing because the PSF of the observation is taken into account through a convolution step, performed to build mock data with the same spatial resolution of the observed ones.

To reproduce the data, the code builds a three-dimensional disc model, formed by N rings of width W, for which the parameters that minimize the residuals between the data cube and the model cube are calculated. These parameters, both geometrical and kinematical, are the rotation velocity $V(R)$, the velocity dispersion $\sigma(R)$, the inclination angle i (90° for edge-on discs), the position angle ϕ of the major axis, the dynamical centre (x_0, y_0), the systemic velocity V_{sys}, the disc scale height z_0, and the gas surface density Σ.

We applied the algorithm to [O III] λ5007 and Hα independently, fixing all the rings parameters except $V(R)$ and $\sigma(R)$. The galaxy was divided into five rings with radii from 0.175 (1.5 kpc) to 1.575 arcsec (13.2 kpc) and a width of 0.35 arcsec, corresponding to about half the PSF. This choice entails that $V(R)$ and $\sigma(R)$ of a ring are not fully independent of the fitted values for the closer ones. The inclination angle i was fixed to 75° for both the lines (see Appendix C) while we chose $\phi = 94°$ after producing pv

Figure 7. Rotation curve of [O III] λ5007 (blue diamonds) and Hα (green circles). The rotation velocity decreases between the first two rings and increases going outwards. The $V(R)$ values are in agreement within the errors for both the lines in all the rings.

diagrams for different position angles and considering the one with the most extended emission. For the dynamical centre we used the coordinates of the emission peak in the *HST/H*-band image while we left the disc scale height z_0 to the default value (150 pc): due to the low spatial resolution the disc scale height is unresolved, hence the thickness has a negligible effect. Finally, we adopted for the gas surface density Σ a locally averaged normalization, in which the flux in each pixel of the disc model is equalled to the flux in the corresponding pixel in the data. In this way the inhomogeneities that may affect a ring, as in the [O III] λ5007 case, can be reproduced.

After setting the disc parameters as described above, we launched ^{3D}BAROLO obtaining two best-fitting model cubes that simulate the [O III] λ5007 and Hα line emission. In order to compare the disc model with the data, we inspected the pv diagrams extracted along the major axis (Fig. 6). The observed [O III] λ5007 and Hα emission is well reproduced by the model. However, some differences are present. For example, the model slightly overestimates the line broadening for both [O III] λ5007 and Hα in the outer rings ($R \sim 1.8$ arcsec) of the approaching side. The disc model also does not reproduce the emission in the central region, with possible repercussions on $V(R)$ and $\sigma(R)$ of the internal rings. This effect is particularly prominent in the Hα case.

The fitted rotation curves nicely show consistent values of $V(R)$ for the two lines in each ring (Fig. 7). The rotation velocity decreases between the first two rings and appears to slightly increase going outwards for both [O III] λ5007 and Hα.

We assessed the reliability of the best-fitting velocities simulating new model cubes in which we varied the fitted $V(R)$ in order to visually verify if different values of the rotation velocity worsened or improved the pv diagram reproduction (see Swaters et al. 2009 for the details about a similar 'trial-and-error' procedure in this context). This test was carried out adopting an azimuthal surface density profile for Σ instead of the local normalization because in this way the simulated pv diagrams present a smoothed and symmetric emission that makes it more straightforward to see variations in their shape. For both [O III] λ5007 and Hα we found that the shape of the pv diagram is not sensitive to large variations of $V(R)$ for the first two rings, meaning that the associated errorbars are underestimated. On the other hand, we consider reliable the

Figure 8. Position-velocity diagrams along the H I wind in the local starburst M82 (Very Large Array and Green Bank Telescope data; Martini et al. 2018). Left-hand panel: original data with a spatial resolution of 0.4 kpc. Right-hand panel: smoothed data with a spatial resolution of 4.65 kpc. The smoothed emission appears roughly similar to the observed velocity gradient of H α and [O III] λ5007 in GMASS 0953 suggesting that the interpretation of gas velocity gradients may be ambiguous when using data of low spatial resolution.

fitted rotation velocity and errors of the external three rings as significantly lower or higher values of $V(R)$ would not reproduce the data.

We repeated the test for the velocity dispersion $\sigma(R)$. The evaluation of this parameter is particularly complex because of the low spatial and spectral resolution of our data and the relatively high inclination of the galaxy. We could derive only an upper limit of $\sigma(R) < 160$ km s^{-1} for [O III] λ5007 and $\sigma(R) < 90$ km s^{-1} for H α at large radii, which we obtained rejecting the $\sigma(R)$ values that do not reproduce the pv diagram.

After this analysis, as a representative rotation velocity of the disc, we took the weighted average $V(R)$ of [O III] λ5007 and H α of the last ring ($R \sim 13$ kpc), which amounts to $V_{\rm ion} = 203^{+17}_{-20}$ km s^{-1}. The associated errors were estimated considering both the fitted ones and the uncertainties due to the inclination angle (see Appendix C).

4.3 An alternative interpretation of the velocity gradient

In Section 4.2 we modelled the kinematics of [O III] λ5007 and H α under the hypothesis that the velocity gradient of the two lines was produced by a rotating disc. This is the more straightforward assumption we can do given the limited spatial resolution of our data. However, velocity gradients in the gas kinematics can also be originated by other phenomena. In particular, galactic-scale winds can produce velocity gradients similar to that observed in GMASS 0953, with the emission coming from the approaching/receding cone blueshifted and redshifted, respectively. This can be seen in observations of local galaxies. One of the best-studied cases of galactic winds in the nearby Universe concerns the starburst galaxy M82. The wind, due to vigorous star formation in the centre, has been observed in several gas phases (e.g. Schaaf et al. 1989; Shopbell & Bland-Hawthorn 1998; Leroy et al. 2015). Recently, Martini et al. (2018) investigated the kinematics of the M82 wind using H I observations resolved on the scale of 0.4 kpc. The wind extends over 10 kpc from the galaxy centre and the observed pv diagram (Fig. 8, left-hand panel) presents some interesting analogies

with those of [O III] λ5007 and H α in GMASS 0953 (Fig. 5). Clearly, a direct comparison of the pv diagrams is difficult because of the different spatial resolution of the two observations. Therefore, we smoothed the M82 data in order to have the same number of resolution elements of GMASS 0953 along the pv diagram. This corresponds to a new spatial resolution of 4.65 kpc. We found that the analogy persists after the smoothing (Fig. 8, right-hand panel) in terms of the global shape of the pv diagram, the asymmetric flux distribution and the observed declining velocity from the inner to the outer regions. Despite these similarities, the above comparison is not trivial at least for two reasons: (i) we are comparing two different gas phases, i.e. ionized versus neutral, which have different physical properties; (ii) we are comparing a local starburst galaxy without AGN activity with a high-redshift active galaxy. Keeping this in mind, our experiment suggests that when looking at the pv diagram of [O III] λ5007 and H α a wind interpretation cannot be ruled out with our data. However, the wind scenario appears quite unlikely in GMASS 0953 since the wind would move along the projected major axis of the galaxy and not in a perpendicular direction, as observed in other low- and high-redshift sources (Heckman, Armus & Miley 1990; Lelli et al. 2018). Moreover, the connection between a putative large-scale wind and the outflow described in Section 6 would remain unclear.

5 THE MULTIPHASE DISC OF GMASS 0953

From the kinematics modelling presented in Section 4.2, it emerges that GMASS 0953 may host an ionized disc extending up to $R \sim 13$ kpc with a rotation velocity $V_{\rm ion} = 203^{+17}_{-20}$ km s^{-1} at the largest radius. The existence of the disc is highlighted by two lines analysed independently, which show two consistent rotation curves. The H α kinematics of GMASS 0953 was modelled also by Wisnioski et al. (2018), who found a rotation curve that is broadly consistent with our estimate at large radii, though a direct comparison between the two rotation curves is made difficult by the differences in the adopted disc modelling and beam smearing correction.

Figure 9. The multiphase gas emission of GMASS 0953 overimposed on the *HST/WFC3* (*H* band) image. The contours refer to the [O III] λ5007 narrow line (cyan), H α (green), and CO(J = 6–5) (orange, ALMA data; Talia et al. 2018). The lowest contour level is at 3σ. The cross indicates the galaxy centre.

Rotation does not concern only the ionized phase of the ISM. According to Talia et al. (2018), GMASS 0953 harbours a very compact ($R_{CO} = 0.75 \pm 0.25$ kpc) molecular disc traced by the CO(J = 6–5) line, with a rotation velocity $V_{CO} = 320^{+92}_{-53}$ km s^{-1}, i.e. higher although compatible at 2σ with our H α inner value. All the three lines show velocity gradients with consistent position angle that are aligned with the major axis of the stellar component. The latter represents possibly a nearly edge-on disc that is visible in the *HST* image of the galaxy (Fig. 9). These findings suggest that GMASS 0953 hosts a multiphase disc, with rotation affecting the galaxy from small to large scales and peaking in its central regions. The joint existence of a cold and an ionized disc in high-z massive galaxies was also found by Übler et al. (2018) and Herrera-Camus et al. (2019). In the very inner region of GMASS 0953, we considered $V_{CO} = 320^{+92}_{-53}$ km s^{-1} of the molecular disc a reliable measure of the rotation velocity. As we discussed in Section 4.2, the internal points of the [O III] λ5007 and H α rotation curve are dominated by large uncertainties and they could be compatible with the CO(J = 6–5) rotation. Declining rotation curves in the central part of galaxies are observed both in local and distant objects (Spekkens & Giovanelli 2006; Noordermeer et al. 2007; de Blok et al. 2008; Genzel et al. 2017). In particular, in local galaxies they have been clearly associated with the presence of large bulges (e.g. Lelli, McGaugh & Schombert 2016a).

The ionized gas also provides the $V(R)$ value on a larger scale, hence we can use it to estimate a lower limit to the dynamical mass of the galaxy. Under the hypothesis of pure circular motions, the dynamical mass contained within the radius $R \sim 13$ kpc amounts to $M_{dyn} = RV_c^2/G > (1.3^{+0.2}_{-0.3}) \times 10^{11}$ M$_\odot$ where, as the circular velocity V_c, we considered the V_{ion} value. Our estimate constitutes only a lower limit to the dynamical mass because the circular velocity V_c may be larger than the fitted rotation velocity V_{ion}. To estimate V_c both H α and [O III] λ5007 may require an asymmetric drift correction (Binney & Tremaine 2008) that is probably negligible for CO(J = 6–5) because of the gas lower

temperature and velocity dispersion. We have not attempted to apply this correction due to the large uncertainties of our velocity dispersion (see Iorio et al. 2017 for the details). The lower limit for the dynamical mass results consistent with the stellar mass evaluated using SED fitting (see Section 2) and also with the upper limit of Förster Schreiber et al. (2009).

It is interesting to see where GMASS 0953 is located on the baryonic Tully–Fisher relation (McGaugh et al. 2000), which connects the baryonic content M_b to the circular velocity. The baryonic content M_b of the galaxy can be evaluated adding the stellar mass $M_\star$ to the gas mass M_g. To compute the gas budget we considered the molecular gas content M_{H_2} evaluated by Talia et al. (2018) and the ionized gas mass M_{ion} derived from the [O III] λ5007 narrow-line luminosity (see Appendix D). However, the latter amounts to $M_{ion} \simeq 8.5 \times 10^6$ M$_\odot$ if we use the observed [O III] λ5007 flux or to $M_{ion} \simeq 2.2 \times 10^8$ M$_\odot$ when correcting for dust extinction, which is in both cases negligible compared to the molecular gas mass $M_{H_2} = (3.24 \pm 0.60) \times 10^{10}$ M$_\odot$ (Talia et al. 2018). We hence computed the baryonic mass as $M_b \simeq M_\star + M_{H_2} = (1.47 \pm 0.12) \times 10^{11}$ M$_\odot$. For the circular velocity we used again V_{ion} at 13 kpc. If we put these two values on the baryonic Tully–Fisher relation of Lelli, McGaugh & Schombert (2016b), we find that GMASS 0953 is well included into the 0.11 dex scatter of the $z = 0$ relation. This result suggests that massive galaxies that are already relaxed at $z \gtrsim 2$ may exist, in agreement with the findings of Lelli et al. (2018).

6 PROBING THE AGN FEEDBACK IN ACTION

6.1 Evidence of an AGN-driven ionized outflow

We know, from what we discussed in Section 3, that the [O III] λ5007 line consists of a narrow component, which we used to model the kinematics, and a broad blueshifted wing fitted in the

GNIRS spectrum that is not ascribable to the rotating disc (Figs 2 and 5). The emitting region appears concentrated near the nucleus of GMASS 0953 (Fig. 3, right-hand panel).

It is interesting to evaluate the size and the velocity of the [O III] λ5007 blueshifted emission. We computed the size of the emitting region through a two-dimensional Gaussian fit on the SINFONI map. The emission appears barely resolved, with a FWHM of the major axis of $\sim$0.8 arcsec, corresponding to 6.7 kpc. The velocity can be evaluated from the line fit of the GNIRS spectrum. We measured the velocity shift between the line centroids of the broad and the narrow [O III] λ5007 line to be $\Delta v = -535 \pm 152$ km s^{-1}.

Line velocity offsets in galaxies are often connected to outflowing gas due to stellar winds or supernova explosions. However, the typical offset in these cases amounts to $|\Delta v| \sim 100$ km s^{-1} (e.g. Shapley et al. 2003; Steidel et al. 2010; Talia et al. 2012), which is considerably lower than our value. Conversely, velocity offsets $\Delta v \sim -500$ km s^{-1} have been found in [O III] λ5007 blueshifted emission extending on several kpc in many high-z active galaxies (e.g. Cano-Díaz et al. 2012; Harrison et al. 2012; Brusa et al. 2015; Carniani et al. 2015). These high-velocity kpc-scale emissions are actually interpreted as robust tracers of AGN-driven outflows and represent an observational evidence of the AGN feedback in action. They are also characterized by line widths >1000 km s^{-1}, compatible with the FWHM $\sim$ 1400 km s^{-1} of the [O III] λ5007 blueshifted line detected in our data. Finally, also the emitting region, located close to the nucleus GMASS 0953, yet supports the AGN activity as the main engine of gas expulsion in this galaxy.

The [O III] λ5007 blueshifted line therefore highlights the presence of an AGN-driven ionized outflow that affects GMASS 0953, suggesting that the AGN feedback is likely at work in this galaxy. A further support to the presence of outflowing material in the ionized phase may come from the blueshifted Hα emission in the central part of the galaxy visible in the pv diagram (Fig. 5, right-hand panel; see also Förster Schreiber et al. 2014; Genzel et al. 2014). Moreover, the FORS2 rest-frame UV spectrum of GMASS 0953 presents absorption lines (e.g. C II λ1334, Si λ1260) that are blueshifted of -800 km s^{-1} with respect to the systemic velocity (Cimatti et al. 2013). This fact suggests the presence of outflowing material also in a lower ionization state than that traced by [O III] λ5007 and Hα. Finally, there is a tentative evidence of a blueshifted wing affecting also the CO(J = 6–5) line with $\Delta v \sim -700$ km s^{-1} with respect to the main component, which might be due to outflowing material in the molecular phase (Talia et al. 2018). However, the low significance of the detection (2.5σ) prevents us to make a reliable analysis of this component hence, to state the effects of gas expulsion on the galaxy, we considered the ionized phase only.

6.2 Impact of the outflow on the host galaxy

6.2.1 Outflow rate

Because of the presence of outflowing gas, it is interesting to evaluate the mass of the expelled material per unit time (i.e. the outflow rate) in order to compare it with the SFR of GMASS 0953. Many studies observed AGN-driven winds in local galaxies with outflow rates that may exceed the SFR (Rupke & Veilleux 2011; Cicone et al. 2014) and influence the star formation activity by removing large amounts of gas.

We followed the approach of Cano-Díaz et al. (2012) and Carniani et al. (2015), who derived the outflow rate of the ionized gas from the luminosity of the [O III] λ5007 blueshifted emission (all the

calculations are in Appendix D). We note that using [O III] λ5007 as a mass tracer of the outflowing gas implies several uncertainties since the derived outflow mass is sensitive to the ionization state and to the metallicity of the gas. The latter cannot be directly measured from the optical line ratios of GMASS 0953 because of the presence of the AGN and we resort to using the mass–metallicity relation (Wuyts et al. 2016) while the ionization state has been assumed (see Appendix D). On the other hand, hydrogen lines such as Hβ and Hα are better mass tracers because they do not depend on these quantities (see Harrison et al. 2018). However, we do not find evidence of a blueshifted wing in the Hβ profile probably because of the low signal-to-noise ratio and the weakness of the emission. In the case of Hα we highlighted in Section 4 the presence of outflowing material possibly shown also by this line; however, the Hα emission suffers from possible contamination of the [N II] $\lambda\lambda$6548, 6584 lines (see Section 3.3) and from the AGN broad-line region (see also Brusa et al. 2015). For these reasons we do not use Hα to derive the outflow properties.

The outflow rate was estimated in two ways: with and without applying the dust extinction correction to the [O III] λ5007 luminosity. As seen in Section 3.1 GMASS 0953 is highly obscured, hence it seems reasonable to consider both scenarios. To evaluate the intrinsic [O III] λ5007 flux, we used the colour excess $E(B - V) = 0.8 \pm 0.3$ derived from the Hα and Hβ line ratio assuming a Calzetti et al. (2000) extinction curve. The resulting ionized outflow mass $M_{\rm of}$ in the extinction corrected case amounts to $M_{\rm of} \simeq 1.2 \times 10^8$ M$_\odot$. Without the extinction correction this quantity drops to $\simeq 4.3 \times 10^6$ M$_\odot$.

Once we have obtained the outflow mass, to evaluate the outflow rate it is necessary to assume a geometrical model to describe the wind. The low spatial resolution of our data does not provide information about the intrinsic geometry of the outflowing gas. For simplicity we used the model of Cano-Díaz et al. (2012), where the ionized gas is distributed in a conical region of radius $R_{\rm of}$ and is expelled in a direction roughly perpendicular to the galaxy disc. Under these assumptions, the outflow rate can be written as

$$\dot{M}_{\rm of} = 3 M_{\rm of} \frac{|v_{\rm of}|}{R_{\rm of}} \tag{1}$$

where $v_{\rm of}$ is the outflow velocity estimated from the line fit of the GNIRS spectrum. There is no general consensus on how to define outflow velocities (see Harrison et al. 2018). In our work we followed the approach of Rupke, Veilleux & Sanders (2005), who defined the outflow maximum velocity as $v_{\rm of} = {\rm FWHM}_{\rm broad}/2 + |\Delta v|$, where the first term is half the FWHM of the [O III] λ5007 blueshifted component and Δv is the velocity offset between the [O III] λ5007 narrow and blueshifted component (see also Fluetsch et al. 2019). The resulting velocity amounts to $v_{\rm of} \sim 1200$ km s^{-1}. Using this $v_{\rm of}$ value in equation (1) we are implicitly assuming that all the outflowing material is moving at this velocity. This could be possible due to projection effects, supported by the high inclination of the galaxy (see also Cano-Díaz et al. 2012; Brusa et al. 2015; Cresci et al. 2015). We note that using a more conservative definition of $v_{\rm of}$, relying on the velocity offset $|\Delta v| \sim 530$ km s^{-1}, the outflow rate would be reduced at most by a factor $\sim$2 and our results would not be considerably modified. Finally, we used as the outflow radius $R_{\rm of}$ half the FWHM of the emitting region visible in the SINFONI map, which amounts to $R_{\rm of} \simeq 3.3$ kpc (see also Harrison et al. 2012, 2014). Substituting these values in equation (1) and using the extinction corrected outflow mass, we found an ionized outflow rate $\dot{M}_{\rm of} \sim 120$ M$_\odot$yr^{-1} that drops to $\sim$6 M$_\odot$ yr^{-1} if the outflow is not extincted by dust.

Figure 10. Comparison between the [O III] λ5007 blueshifted line (cyan) and the dust continuum (red, ALMA data; Talia et al. 2018). The two emissions are both concentrated near the centre of GMASS 0953, marked with a cross.

An indication of whether the outflow is affected or not by dust obscuration may come from the 1.4 mm continuum of GMASS 0953 (Talia et al. 2018), which is a robust tracer of dust. After applying an astrometric correction (see Appendix A), we overlapped the dust continuum map on the outflow emission detected with SINFONI (Fig. 10). Interestingly, the dust and the [O III] λ5007 blueshifted component emit in the same region. Therefore, it is plausible that the [O III] λ5007 luminosity may be dimmed by the dust along the line of sight, though it is also possible that the outflow may have already escaped the dusty region of the galaxy because of the high velocity.

Apart from the extinction correction and the adopted assumption about the outflow velocity, it should be noted that other uncertainties affect the outflow rate. The derivation of the outflow mass M_{of} that enters equation (1) requires the knowledge of the electron number density of the gas (see Appendix D). This quantity was derived from the [S II] λλ6716, 6731 line ratio and amounts to 500 cm^{-3} (see Section 3.1). Unfortunately, the [S II] λλ6716, 6731 emission is produced by the galaxy ISM and not by the wind since we did not find evidence of a broad component in the [S II] λλ6716, 6731 line fit likely because of the low signal-to-noise ratio. Finally, we remind that we assumed a conical outflow for simplicity, but the true geometry is not known.

6.2.2 Depletion time-scale

In order to properly gauge the impact of the AGN feedback on GMASS 0953 a comparison between the depletion time-scale due to star formation with that associated with gas ejection is necessary. The former amounts to $\tau_{dep}^{SF} = M_{H_2}/SFR \sim 150$ Myr (Popping et al. 2017; Talia et al. 2018). The depletion time-scale due to the outflow can be evaluated as the ratio between the mass of the ionized gas and the outflow rate, i.e. $\tau_{dep}^{OF,ion} = M_{ion}/\dot{M}_{of} \sim 2$ Myr (extinction corrected case). This very short value is however implausible if the outflowing material is supplied by the internal gas reservoir of the

galaxy, which is much higher than M_{ion}. Under the assumption that the outflow is depleting the whole ISM, we can write the depletion time-scale as $\tau_{dep}^{OF,mol} \approx M_{H_2}/\dot{M}_{of}$, which is ~ 270 Myr using again the extinction corrected [O III] λ5007 luminosity. We note that this value of $\tau_{dep}^{OF,mol}$ represents an estimate of the depletion time-scale in the central region only, since the molecular gas is concentrated within a radius of 1 kpc (Talia et al. 2018). From the comparison of the depletion time-scales, it appears that the AGN-driven outflow and the star formation activity contribute in a similar way in depleting the gas reservoir of the galaxy. We note however that the outflow would be much less effective in consuming the gas if the not-extincted value of the [O III] λ5007 luminosity were considered. Using the not-extincted luminosity we obtain indeed a depletion time-scale $\tau_{dep}^{OF,mol} \sim 5.4$ Gyr, meaning that the AGN-driven outflow is negligible compared to the star formation activity. Moreover, the latter may also drive galactic winds that would provide an additional contribution to gas consumption from star formation (Heckman & Thompson 2017).

Apart from the extinction correction, another important uncertainty affects the outflow depletion time-scale. We considered in the evaluation $\tau_{dep}^{OF,mol}$ the contribution of the ionized outflow only. Many studies show that this phase cannot be the dominant constituent of AGN outflows (Fiore et al. 2017); in particular, molecular outflows were found to be up to two orders of magnitude more massive than ionized outflows in active galaxies where both the phases have been observed (Carniani et al. 2015). As we mentioned in Section 6.1, we did not find evidence of outflowing material in the molecular phase except for a feature of 2.5σ blueshifted from the CO(6–5) main line. The ALMA data can be used to set an upper limit to the molecular outflow rate of GMASS 0953. We stacked the channels between −500 and −1200 km s^{-1}, corresponding to the outflow emission in the SINFONI data (see Fig. 5, middle panel), in order to derive a 3σ upper limit to the flux density of the CO(6–5) outflow ($S_{CO}^{3\sigma} = 79$ mJy, assuming the outflow has the same size of the ionized one; see also Brusa et al. 2018). This value was

converted in H_2 mass using the same assumptions of Talia et al. (2018). We hence derived an upper limit to the molecular outflow rate using equation (1) and adopting the same velocity of the ionized outflow. The upper limit to the molecular outflow rate amounts to $\sim 2500 \, M_\odot \, yr^{-1}$. This means that our observation does not allow us to detect outflow rates below this quantity, which can potentially contribute to gas consumption.

From the reported analysis we conclude that the role played by the AGN feedback in GMASS 0953 is quite unclear. However, despite the aforementioned uncertainties, the galaxy appears a promising candidate to quench the star formation activity in a total depletion time-scale $\tau_{dep}^{TOT} = M_{H_2}/(SFR + \dot{M}_{of}) \sim 10^8$ yr (see also Brusa et al. 2018) if the accretion from external gas is shutdown. This estimate is valid in both the extinction corrected/not-corrected case.

7 CONCLUSIONS

In this work we studied the kinematics of the active galaxy GMASS 0953 from a multiwavelength perspective. Our analysis was focused on the [O III] $\lambda 5007$ and Hα emission lines, which we inspected combining three spectroscopic data set. The main conclusions of our work are summarized here:

(i) We found evidence of a multiphase disc supported by the [O III] $\lambda 5007$, Hα and CO(J = 6–5) emission lines, which have parallel velocity gradients extending in the same direction of the stellar component. We investigated the kinematics of [O III] $\lambda 5007$ and Hα independently using a three-dimensional modelling that corrects for beam smearing. The two lines present consistent rotation curves with an average rotation velocity $V_{ion} = 203^{+17}_{-20}$ km s^{-1} at a distance of 13 kpc from the galaxy centre. As already known, the CO(J = 6–5) traces rotation on a much smaller scale ($R \sim 1$ kpc) with a rotation velocity $V_{CO} = 320^{+92}_{-53}$ km s^{-1} (Talia et al. 2018). Combining these two results, the arising picture is that GMASS 0953 may host a multiphase disc with a rotation curve peaking in the central regions and a dynamical mass $> 1.3 \times 10^{11} \, M_\odot$, consistent with the stellar mass. The galaxy falls onto the 0.11 dex scatter of the $z = 0$ baryonic Tully–Fisher relation of Lelli et al. (2016b), suggesting that it is already kinematically relaxed. On the other hand, the velocity dispersion of the disc of GMASS 0953 is poorly constrained by our kinematic model because of the low spatial resolution of the SINFONI and KMOS data.

(ii) Based on the analogies between the [O III] $\lambda 5007$ and Hα pv diagrams of GMASS 0953 and the local starburst M82, we also discussed the possibility of a galaxy-scale wind as an explanation of the observed gradient. Despite finding this scenario unlikely, we caution the reader over the challenging interpretation of gas velocity gradients in data with low spatial resolution.

(iii) We discovered an ionized outflow extending on kpc-scale and likely associated with the nuclear activity of GMASS 0953. The outflow was highlighted by a broad (FWHM ~ 1400 km s^{-1}), blushifted wing in the [O III] $\lambda 5007$ line profile with a velocity shift of $\Delta v = -535 \pm 152$ km s^{-1} from the systemic velocity. The blueshifted [O III] $\lambda 5007$ emission was detected independently by the GNIRS and SINFONI spectrographs. Other hints of outflowing material in the ionized phase come from the position-velocity diagram of Hα presented in this work (see also Förster Schreiber et al. 2014; Genzel et al. 2014) and the UV absorption lines (Cimatti et al. 2013).

(iv) We derived the outflow rate of the ionized gas in order to assess the impact of the AGN feedback on the galaxy. We found that the outflow rate amounts to $\sim 120 \, M_\odot \, yr^{-1}$, which drops to

$\sim 6 \, M_\odot \, yr^{-1}$ without applying the dust extinction correction. We compared the gas depletion time-scale due to the outflow with the one based on star formation finding that they are of the same order of magnitude (extinction corrected case). When both processes are considered we find a total depletion time-scale of 10^8 Myr. This means that GMASS 0953 is expected to rapidly quench the star formation activity, if the accretion of external gas is shutdown. However the role played by the AGN in this galaxy appears unclear due to the several uncertainties affecting the outflow rate. For example, if the outflow luminosity is not extincted by dust, the depletion time-scale associated with the outflow drops to 5.4 Gyr, negligible compared to that due to star formation ($\tau_{dep}^{SF} \sim 150$ Myr). Besides, using our data we can only constrain the ionized phase while we are not accounting for possible gas expulsion in other phases (e.g. molecular). Deeper ALMA observations will be crucial in this sense.

Despite the remaining open questions, we stress the importance of multiwavelength and multi-instrument studies of high-z galaxies. They provide complementary details about the ISM that are essential to characterize the processes occurring in $z \sim 2$ massive systems. Even though the uncertainties due to the observational limits of high-z sources, multiwavelength studies represent the most powerful approach to investigate the kinematics of $z \sim 2$ galaxies and the role played by AGNs in their evolution.

ACKNOWLEDGEMENTS

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APPENDIX A: ASTROMETRIC CORRECTIONS

We verified the astrometry of the SINFONI data against the *HST* imaging of GMASS 0953. In order to properly overlap the maps of [O III] λ5007 on the *HST* images, we adjusted the data cube coordinates imposing the matching between the peak of the SINFONI stacked continuum and the light peak determinated in the *HST/H*-band image. The coordinates of the peaks were both calculated through a two-dimensional Gaussian fit. The correction resulted in a shift of $+1.26$ arcsec in RA and $+2.16$ arcsec in Dec. applied to the data cube coordinates, after which we could nicely superimpose the SINFONI line maps on the *HST* images (Fig. 9).

We verified also the astrometry of the ALMA data with respect to the *HST* images of GMASS 0953. The systematic offset between ALMA and the *HST* data in the GOODS-South is a well-known problem that was underlined in many works (e. g. Maiolino et al. 2015, Dunlop et al. 2017). We applied the correction of Franco et al. (2018) determined for the object AGS13: this name refers indeed to GMASS 0953, which was studied also in that work. We shifted the coordinates of -0.087 arcsec in RA and $+0.291$ arcsec in Dec. In this way we could correctly overlap the dust continuum of the galaxy on the *HST* images of GMASS 0953 (Fig. 10).

Figure B1. Line fit of H α and [N II] λλ6548, 6584 (KMOS data). Each spectrum was extracted from a pixel belonging to a section of 5 × 5 pixels, which corresponds to the central region of GMASS 0953. We modelled the data (blue line) with three Gaussian components and a linear continuum (coloured lines). The centroids ratio of the [N II] λλ6548, 6584 doublet and H α was fixed to the theoretical one. We imposed the same FWHM for the nitrogen lines and their flux ratio was fixed to 1:3. The total model is overlayed in red.

APPENDIX B: KMOS LINE FITTING

In order to study the kinematics of the H α line, it was necessary to separate its emission from the [N II] λλ6548, 6584 doublet, which is blended with H α, and to subtract the stellar continuum. A line fit was hence performed in each pixel of the KMOS data cube containing the stellar and [N II] λλ6548, 6584 emission (Fig. B1). We selected a region of 5 × 5 pixels corresponding to the galaxy central part because the nitrogen and the stellar emission were mainly confined in a region of this size (∼6.7 kpc). For each pixel we extracted a spectrum that was modelled with three Gaussians and a linear continuum. The centroids ratio of the [N II] λλ6548, 6584 doublet and H α was fixed to the theoretical one (0.995 for the [N II] λλ6548, 6584 lines and 0.998 for the [N II] λ6548 and H α ratio); we also imposed the same FWHM for the nitrogen lines and fixed

their intensity ratio to 1:3.[6] We then subtracted from each pixel in the data cube the corresponding [N II] λλ6548, 6584 models and the continuum level. In this way we obtained a data cube that contains only the H α emission, which was used to study the kinematics.

APPENDIX C: INCLINATION ANGLE

The disc inclination in the ^{3D}BAROLO model was determined by comparing the shape of the H α total flux map with synthetic maps obtained for fixed inclination angles (from 60° to 85°) using an azimuthally averaged H α surface brightness profile (Fig. D1). We

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[6]We executed also a fit in which the intensity ratio of [N II] λλ6548, 6584 was left free, but it showed no significant differences.

used the Hα line instead of [O III] λ5007 because of the higher flux of the receding half, which allows to better examine the geometry of the disc. This (by eye) comparison allowed us to exclude inclination angles lower than 70° and greater than 80° and as a fiducial average value we took $i = 75°$ for all the rings. The reliability of our choice was confirmed by the residuals between the data and the model evaluated for different inclination angles, which show a minimum corresponding to $i = 75°$. Therefore we fixed $i = 75°$ for both the [O III] λ5007 and Hα disc models. We considered the uncertainty due to the inclination angle in the range $70° < i < 80°$ when we calculated the errorbars of the [O III] λ5007 and Hα rotation velocity. However, given the high value of i, the uncertainty on the inclination does not have a big impact on the derived rotation velocity.

APPENDIX D: OUTFLOW MASS AND OUTFLOW RATE

To evaluate the outflow mass and the outflow rate traced by [O III] λ5007 we followed the approach of Cano-Díaz et al. (2012) and Carniani et al. (2015). We started evaluating the outflow mass, i.e. the total mass of the ionized gas expelled, from the luminosity of the [O III] λ5007 blueshifted component. The luminosity of the [O III] λ5007 line can be written as

$$L_{\text{[O III]}} = \epsilon_{\lambda 5007} f V_{\text{of}}, \tag{D1}$$

where $\epsilon_{\lambda 5007}$ is the line emissivity, V_{of} the total volume occupied by the ionized outflow, and f is the filling factor, i. e. the ratio between the volume of the [O III] λ5007 emitting gas and the total volume: we worked indeed under the hypothesis that the [O III] λ5007 line is produced by a fraction of the outflowing ionized gas. We used the emissivity value reported by Cano-Díaz et al. (2012) for a temperature $T = 10^4$ K

$$\epsilon_{\lambda 5007} = 1.11 \times 10^{-9} h\nu_{\lambda 5007} n_{\text{O}^{2+}} n_{\text{e}} \quad [\text{ erg s}^{-1}\text{cm}^{-3}], \tag{D2}$$

where $n_{\text{O}^{2+}}$ is the number density of the doubly ionized oxygen and n_{e} the electron number density. Under the reasonable assumption that all the oxygen is in the ionized form, we can espress $n_{\text{O}^{2+}}$ as

$$n_{\text{O}^{2+}} = \frac{n_{\text{O}}}{n_{\text{H}}}\frac{n_{\text{H}}}{n_{\text{e}}}n_{\text{e}}, \tag{D3}$$

where n_{O} and n_{H} are the neutral oxygen and hydrogen number densities. The electron number density n_{e} can be written as $n_{\text{e}} \approx n_{\text{H}^+} + 1.5n_{\text{He}}$ for a helium mixture made up by equal parts of He$^+$ and He^{++} (Osterbrock & Ferland 2006). Since the number density of the ionized helium n_{He} is in good approximation $0.1n_{\text{H}^+}$, under the hypothesis that $n_{\text{H}} \approx n_{\text{H}^+}$, equation (D3) becomes

$$n_{\text{O}^{2+}} = \frac{n_{\text{O}}}{n_{\text{H}}}(1.15)^{-1}n_{\text{e}} = 10^{\log\left(\frac{n_{\text{O}}}{n_{\text{H}}}\right)_\odot}10^{\left[\frac{O}{H}\right]}(1.15)^{-1}n_{\text{e}}, \tag{D4}$$

where $\left[\frac{O}{H}\right] \equiv \log\left(\frac{n_{\text{O}}}{n_{\text{H}}}\right) - \log\left(\frac{n_{\text{O}}}{n_{\text{H}}}\right)_\odot$ is the metallicity. Substituting equation (D4) in equation (D2) and equation (D1) we obtain

$$L_{\text{[O III]}} = 4.727 \times 10^{-13} h\nu_{\lambda 5007} n_{\text{e}}^2 10^{\left[\frac{O}{H}\right]} f V_{\text{of}} \quad [\text{ erg s}^{-1}]. \tag{D5}$$

We used for the oxygen abudance of the sun $(n_{\text{O}}/n_{\text{H}})_\odot$ the value of Asplund et al. (2009). If we neglect the elements heavier than helium, the ionized gas mass M_{of} of the [O III] λ5007 emitting clouds is essentially given by

$$M_{\text{of}} = (n_{\text{H}^+}m_{\text{p}} + n_{\text{He}}m_{\text{He}}) f V_{\text{of}}, \tag{D6}$$

Figure D1. Comparison between the Hα flux map (black contour and colours) and the model maps (red contour, 3σ level) obtained using an azimuthally averaged Hα profile for fixed inclination angles. The inclination angle was varied from $i = 60°$ to $i = 85°$. We report here the models corresponding to $i = 65°$ and $i = 85°$ (top and bottom panel) and the one with $i = 75°$ (middle panel), which we fixed as the disc inclination. The more plausible inclination angles are included in the range $70° < i < 80°$ while for $i < 70°$ and $i > 80°$ the model varies significantly from the data.

where m_{p} and m_{He} are the proton and helium mass. Since $m_{\text{He}} \approx 2m_{\text{p}}$ and expressing n_{H^+} and n_{He} in terms of n_{e}, equation (D6) becomes

$$M_{\text{of}} = 1.04 \, n_{\text{e}}m_{\text{p}} f V_{\text{of}}, \tag{D7}$$

which combined with equation (D5) gives

$$M_{\text{of}} = \frac{1.04 \quad m_{\text{p}}}{4.727 \times 10^{-13} h\nu_{\lambda 5007} n_{\text{e}} 10^{\left[\frac{O}{H}\right]}} L_{\text{[O III]}} \quad [\text{ g }]. \tag{D8}$$

We measured the electron number density n_{e} from the [S II] $\lambda\lambda$6716, 6731 line ratio (see Section 3.1). The metallicity was derived using the mass–metallicity relation of Wuyts et al. (2016) and amounts to $\left[\frac{O}{H}\right] = \log(0.9)$ for a stellar mass of 10^{11} M$_\odot$.

Once we have the outflow mass we can evaluate the outflow rate, i.e. the ionized gas mass expelled per unit time. In order to

calculate it, we adopted a simple geometrical model to describe the outflow, as done by Cano-Díaz et al. (2012), where the material is distributed in a conical region with an opening angle Ω and radius R_{of} and is expelled in a direction almost perpendicular to the galaxy disc. Under this assumption, the outflow rate can be written as

$$\dot{M}_{\mathrm{of}} = \rho v_{\mathrm{of}} \Omega R_{\mathrm{of}}^2, \tag{D9}$$

where ρ is the mass density of the ionized gas and v_{of} the outflow velocity. Assuming that the ejected material is located in a volume $V_{\mathrm{of}} = \frac{4}{3}\pi R_{\mathrm{of}}^3 \frac{\Omega}{4\pi}$ and simply writing ρ as $\rho = M_{\mathrm{of}}/V_{\mathrm{of}}$, equation (D9) becomes

$$\dot{M}_{\mathrm{of}} = 3 M_{\mathrm{of}} \frac{v_{\mathrm{of}}}{R_{\mathrm{of}}} \tag{D10}$$

by which it is possible to estimate the outflow rate of the ionized gas.

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