Chapter 6

Probing multi-phase outflows and AGN feedback in compact radio galaxies: the case of PKS B1934-63

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Abstract

Young radio AGN are pivotal for our understanding of many of the still debated aspects of AGN feedback. In this chapter we present a study of the interstellar medium (ISM) in the compact, peaked-spectrum radio galaxy PKS B1934-63 using X-shooter observations. Most of the warm ionized gas resides within a circum-nuclear disk with a radius of about 200 pc that is likely to constitute the gas reservoir from which the central black hole feeds. On the other hand, we find a bi-conical outflow of warm ionized gas with an estimated radius of $59 \pm 12$ pc. This matches the radial extent of the radio source and suggests that the outflow is jet-driven. Thanks to the superior wavelength coverage of the data, we can estimate the density of the warm ionized gas using the transauroral line technique and we find that the outflowing gas has remarkably high density, up to $\log n_e (\text{cm}^{-3}) \simeq 5.5$. The estimated mass outflow rate is low ($\dot{M} = 10^{-3} - 10^{-1} \text{ M}_\odot \text{ yr}^{-1}$) and the AGN feedback is operating at relatively low efficiency ($\dot{E}/L_{\text{bol}} \sim 10^{-4} - 10^{-3}\%$).

In addition, optical and near-IR line ratios show that the expansion of the radio source is driving fast shocks (with velocities $v_s \gtrsim 500 \text{ km} \text{ s}^{-1}$) which ionize and accelerate the outflowing gas.

At odds with the properties of other compact, peaked-spectrum radio sources hosting warm ionized gas outflows, we do not find signs of kinematically disturbed or outflowing gas in phases colder than the warm ionized gas. We argue that this is due to the young age of our source, and thus the recent nature of the AGN-ISM interaction, and suggest that cold gas forms within the outflowing material and the shock-ionized outflowing gas of PKS B1934-63 did not have enough time to cool down, and accumulate in a colder phase. This scenario is also supported by the multi-phase outflows of other compact and young radio sources in the literature.
6.1 Introduction

The interaction between the energy released by the central active nucleus (AGN) and the host galaxy’s interstellar medium (ISM) is particularly prominent in compact and young radio galaxies, and one of its main manifestations are jet-driven gas outflows extended on scales of galaxy bulges (see e.g. Fanti et al. 1990; Fanti & Fanti 1994; Axon et al. 2000; O’Dea et al. 2002; Holt et al. 2006, 2008; Geréb et al. 2015a, b). In the context of galaxy evolution, the negative feedback effect that such outflows, and thus AGN, have on the host galaxy has a crucial role in explaining, for example, scaling relations between the central black hole (BH) and its host galaxy properties (Silk & Rees 1998; Fabian 1999; King 2003; Granato et al. 2004; Di Matteo et al. 2005) and the quenching of the star formation (Benson et al. 2003; Bower et al. 2006; Bongiorno et al. 2016) in massive early-type galaxies (ETG).

Compact and young radio galaxies are identified by the (small) size of their radio emission and, based on the properties of their radio spectra, are classified as Compact Steep Spectrum (CSS) or as GigaHertz Peaked Sources (GPS) (e.g. Giroletti & Polatidis 2009; Murgia et al. 1999; Murgia 2003). Many compact radio galaxies show clear signs of the interaction between the expanding radio jets and the surrounding dense, and multi-phase, ISM which slows down (or even prevents) the jet expansion (see Orienti & Dallacasa 2008; Callingham et al. 2015; Tingay et al. 2015, and reference therein), in line with the predictions of simulations (Bicknell et al. 1997; Wagner et al. 2012, 2016).

These newly-born AGN inflating their radio lobes into the surrounding ISM give us the unique opportunity to study many aspects of so-called AGN feedback. In particular, they can help us to probe the efficiency of the AGN feedback in different gas phases and, even more, investigate the origin of the cold gas which is often observed in this harsh environment (see e.g. Dasyra & Combes 2012; Tadhunter et al. 2014; Oosterloo et al. 2017). Currently the acceleration mechanism of outflows is uncertain and these sources are ideal for probing the relevance that shocks have in accelerating and ionizing outflowing gas.

Even though their actual impact is still unclear, ionized gas outflows are commonly found in compact, young radio sources, and show more extreme features compared to the outflows in extended radio sources (Holt et al. 2008). In the case of the warm ionized gas, one of the important parameters
which contributes to the uncertainties in the estimate of the outflow efficiency is the gas electron density $n_e$ (see Tadhunter 2016; Harrison et al. 2018, for a discussion). The classical line ratios used as density diagnostic, like the $\text{[SII]} \lambda 6717/\lambda 6731$ Å ratio, give a reliable estimate only for low densities ($10^2 < n_e < 10^{3.5} \text{ cm}^{-3}$) and saturate in the high density regime (see Osterbrock & Ferland 2006). These low densities might not reflect the actual gas properties, especially in the case of compact radio galaxies, and might result in incorrect values for the mass outflow rate and the outflow efficiency. Holt et al. (2011) and Rose et al. (2018) make use of the technique based on the $\text{[SII]}$ and $\text{[OII]}$ transauroral lines and find that the gas electron density can reach values up to $n_e = 10^{4-5} \text{ cm}^{-3}$ for outflowing gas.

The occurrence and effects that shocks have on the ISM is also an important, albeit poorly quantified, component of AGN-driven outflows. It is known that both fast radio jets/lobes and AGN winds are able to shock and accelerate the ambient ISM along their path (see e.g. Couto et al. 2013, 2017). Evidence and/or indications of the presence of shocks have often been reported for compact radio sources and they are usually connected to the expansion of the radio source within the ambient ISM. The main evidence for shocks comes from Hubble Space Telescope high-resolution imaging studies of the warm ionized gas (de Vries et al. 1997b; Axon et al. 2000; Batcheldor et al. 2007; Labiano 2008) which, in some cases, have been complemented by spectroscopic observations of highly broadened emission lines (Holt et al. 2008). In other cases, kinematically disturbed cooler ISM phases (neutral and molecular) have been found at the location of radio lobes, clearly indicating shock acceleration (e.g. Oosterloo et al. 2000; Morganti et al. 2013; Tadhunter et al. 2014; Oosterloo et al. 2017). Mainly due to limitations in the observations, pure spectroscopic evidence of shock-ionized gas is sparse and much harder to find.

Finally, outflows of atomic (H$^1$) and molecular (warm H$_2$ and CO) gas have been observed in compact steep-spectrum radio sources like IC 5063 (Tadhunter et al. 2014; Morganti et al. 2015), PKS B1345+12 (Morganti et al. 2013; Dasyra & Combes 2012) and 3C 305 (Morganti et al. 2005a). However, the origin of the cold outflowing gas it is still not clear in the context of AGN feedback. A scenario that is gaining consensus predicts that molecular gas forms in-situ, in particular in the post-shock regions of the outflows, rather then surviving the AGN-ISM interaction and being gradually accelerated by entrainment. This is supported by the molecular
gas observations of the compact radio source IC 5063 (see Tadhunter et al. 2014; Morganti et al. 2015) and by recent simulations by Richings & Faucher-Giguere (2017), showing that cold gas can form in the first few $10^5$ yr after the start of the AGN-ISM interaction. Compact radio sources, with their young age and multi-phase outflows, are ideal objects to test this scenario.

In this chapter, we use spectroscopic observations of the compact radio source PKS B1934-63 to characterize the efficiency of the AGN feedback for the warm ionized gas phase and compare it to other classes of objects. We also study the presence/relevance of shocks using line ratio diagnostics, and investigate the multi-phase nature of the outflowing gas using the emission of the warm molecular gas. Finally, we perform a first attempt to test the scenario in which cold gas forms within the post-shock regions of outflows by combining our findings with the results already available in literature for other compact radio sources.

6.1.1 PKS B1934-63

PKS B1934-63 (z=0.1824) is a powerful radio AGN ($P_{1.4\text{GHz}} = 10^{27.2}$ W Hz$^{-1}$) classified as a GPS by de Vries et al. (1997a). It has often been often considered as the archetypal GPS source: it is among the closest and most powerful compact radio sources and was one of the first GPS to be discovered (Bolton et al. 1963). Very Long Baseline Interferometry (VLBI) observations resolved the radio source in two components, likely representing the two radio lobes, separated by $131.7 \pm 0.9$ pc (Ojha et al. 2004). The kinematic age of the radio source has been estimated to be $1.6 \times 10^3$ yr by monitoring the lobe separation over a timescale of about 32 yr (Ojha et al. 2004).

The host galaxy of PKS B1934-63, identified by Fosbury et al. (1987), is an ETG which is undergoing a merger with a companion galaxy located about 9 kpc away. Optical and infrared images revealed the fainter companion together with clear tidal features (Heckman et al. 1986; Inskip et al. 2010; Ramos Almeida et al. 2011). The optical polarimetry study of Tadhunter et al. (1994b) found polarized light consistent with scattered AGN light, or with non-thermal emission connected to the radio structure.

More recently, Holt et al. (2008) and Roche et al. (2016) studied the conditions of the warm ionized gas in the host galaxy using slit and integral field spectroscopy respectively. Both studies reported the presence of a
broad blueshifted component in the $[\text{O III}]\lambda 5007\text{Å}$ line profile representing outflowing gas, and hints of high gas densities (measured via the classical $[\text{S II}]\lambda 6717/\lambda 6731\text{Å}$ line ratio). Moreover, Roche et al. (2016) found that the outflowing gas component has a velocity gradient aligned with the radio jets, and suggested the presence of shocks as the mechanism which ionizes the warm ionized gas.

Here, we present long-slit spectroscopic observations of PKS B1934-63 obtained with the X-shooter instrument (Vernet et al. 2011) mounted at the VLT. We take advantage of the large wavelength coverage and of the good velocity resolution of the X-shooter data to study the presence of outflowing gas and probe the warm ionized gas electron density via the transauroral line technique (Sec. 6.3). In addition, using the spectro-astrometry technique, we study the spatial extent of the different kinematical components of the ionized gas (Sec. 6.4). This allows us to obtain a better estimate of the mass outflow rate and of the efficiency of the AGN feedback (Sec. 6.5). We also investigate the ionization state of the warm ionized gas using line ratio diagnostic diagrams to probe the presence of shocks within the outflowing material (Sec. 6.6). Finally, we study the kinematics of the warm molecular gas and link it to the kinematics of the warm ionized and atomic gas (Sec. 6.7).

Throughout this chapter we assume the following cosmology: $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_0 = 0.28$ and $\Omega_\Lambda = 0.72$. At the redshift of PKS B1934-63 1 arcsec=3.091 kpc.

6.2 Observations and Data Reduction

Observations were carried out with X-shooter at the VLT/UT2 on July 1st 2011 in visitor mode and with a total exposure time of 75 min (i.e. $10 \times 450$ sec for the visual arm (VIS), $5 \times 900$ sec for the ultraviolet-blue arm (UVB), $15 \times 300$ sec for the near-infrared arm (NIR)). In order to facilitate sky subtraction, separate exposures were taken with the slit nodded off source. The instrument was used in SLIT mode with $1.6\times11$ arcsec slit for the UVB arm, $1.5\times11$ arcsec slit for the VIS arm and $1.5\times11$ arcsec slit for the NIR arm. The selected slit position angle (PA) was set to be 104 degrees (from North to East), close to the PA of the source’s radio axis (i.e. 90 degrees, Tzioumis et al. 1989) and including both PKS B1934-63 host galaxy and the fainter merging/interacting companion.
To estimate the seeing, we used three sets of acquisition images taken during the observations, measuring the profiles of seven stars in the images. For each star we extracted a spatial profile, using a mock slit with the same size of the slit used for the actual observations, and we fitted it with a Gaussian function. The seeing was then estimated taking the average full width at half maximum (FWHM) of the fitted 1D profiles. In this way we obtained a seeing value of $0.97 \pm 0.06$ arcsec that takes into account the integration of the seeing profile across the slit in the dispersion direction. The uncertainty in the seeing is the standard error of all the seeing values extracted from the acquisition images.

Standard data reduction was performed by using the ESO REFLEX workflow and included bias subtraction, flat fielding and flux calibration. For each arm, we applied second-order calibrations to the final pipeline products. Residual hot and bad pixels were removed using FIGARO BCCLEAN. Sky subtraction was performed on the slit spectra by extracting an average sky spectrum from the regions of the slit devoid of sources (i.e. the top and bottom part of the slit). We also performed a telluric absorption-line correction using the integrated spectrum of a standard star observed during the same night.

We derived the average accuracy of the wavelength calibration and the average instrumental width by measuring the line centers and FWHM of sky emission lines respectively. We found that the wavelength calibration accuracy is $20 \, \text{km} \, \text{s}^{-1}$, $5 \, \text{km} \, \text{s}^{-1}$ and $3 \, \text{km} \, \text{s}^{-1}$, while the instrumental
width is 90 km s\(^{-1}\), 60 km s\(^{-1}\) and 90 km s\(^{-1}\) for the UVB, VIS and NIR arms respectively. The relative flux calibration accuracy was estimated to be 10% taking into account the flux variations of the source calibrated using three different standard stars from the same night.

Considering that the radio source is 42.6±0.3 mas in diameter (i.e. spatially unresolved by the current observations) we used the estimated seeing to set the aperture size and extract the nuclear spectrum of PKS B1934-63 (see Fig. 6.1).

6.3 Data Analysis and Results

The nuclear spectrum of PKS B1934-63 (shown in Fig. 6.1 for the UVB and VIS bands) is extremely rich in emission lines with complex line profiles. The spectrum shows typical features of an high-excitation radio source (HERG, Best & Heckman [2012]) with in addition strong low ionization lines such as the [O\(\text{I}\)], [O\(\text{II}\)] and [S\(\text{II}\)] lines. We also detect absorption features for the Mg\(\text{II}\)\(\lambda\lambda\)2796,2804\AA\ in the UVB, and H\(\text{2}\) emission lines in the NIR. We find that the strongest emission lines show broad wings and are double peaked. This, together with the line modelling, will be discussed in more detail in Sec. 6.3.2.

6.3.1 Redshift and stellar population modeling

Deriving an accurate value for the redshift of the galaxy is essential for the determination of the velocity of any outflowing gas component. The available estimate of the host galaxy systemic velocity is based on bright AGN emission lines (Holt et al. [2008]). These lines are often affected by the complex kinematics of the ionized gas, leading to uncertainties in the derived systemic velocity (Tadhunter et al. [2001] Comerford et al. [2009]).

With our current data we could estimate the systemic redshift of the galaxy using the Ca\(\text{II}\) K stellar absorption (part of the Ca\(\text{II}\)\(\lambda\lambda\)3933,68\AA\ doublet) which is free from the contamination of gas emission lines. We fitted this line with a Lorentzian function and obtained a redshift \(z = 0.18240 \pm 0.00013\) (the uncertainty on the redshift corresponds to about 40 km s\(^{-1}\)).

However, the Ca\(\text{II}\) K stellar absorption can potentially include absorption due to the ISM of the host galaxy. To verify that this did not have a significant impact on our redshift estimate, we used the ISM absorption
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lines of the \( \text{Mg II} \lambda \lambda 2795,2802 \text{Å} \) doublet. We found that the width of the \( \text{Mg II} \) absorption lines was significantly lower than the one of the \( \text{Ca II} \ K \) absorption (about 7 times lower) and their velocity shift was compatible, within the errors, with the systemic velocity derived from the \( \text{Ca II} \ K \) absorption (see Appendix 6.A for the details on the fitting procedure). Therefore, we concluded that the \( \text{Ca II} \ K \) absorption line profile is mainly related to stellar absorption and that our estimate of the redshift is robust.

We modelled the stellar population in the nuclear spectrum of the host galaxy using STARLIGHT (version 04, Cid Fernandes et al. 2005) and masking all the emission lines. With the aim of finding a simple model to fit the continuum emission, we used stellar templates with solar metallicity provided by STARLIGHT (Bruzual & Charlot 2003) to model the stellar light. Given that Tadhunter et al. (1994b) detected scattered light from the central AGN we also introduced a power-law (\( F_\lambda = \lambda^\alpha \)) in our model to take this into account. The best model of the galaxy continuum was chosen based on \( \chi^2 \) statistics and residual analysis. It includes a 2.5 Gyr old stellar population and a power-law with spectral index \( \alpha = -0.1 \). The redshift derived from the stellar population fit procedure is in line with our redshift estimate using the \( \text{Ca II} \ K \) absorption line. Our best model is shown in Fig. 6.11 in Appendix 6.A and was subtracted from the nuclear spectrum of PKS B1934-63 before performing the modelling of the gas emission lines.

6.3.2 The emission lines model

To obtain a reference model for the forbidden emission lines of the ionized gas, we shifted the spectrum to the galaxy rest-frame and use the \([\text{O III}] \lambda \lambda 4958,5007 \text{Å} \) doublet. Each line of the doublet is double peaked and has broad wings (see Fig. 6.2), clearly requiring multiple components to be modelled. All our fits were performed using Gaussian functions and custom-made IDL routines based on the MPFIT (Markwardt 2009) fitting routine. For each component of the doublet we forced the width of the Gaussians to be the same, in addition we fixed their separation (49 Å) and their relative fluxes (1:3).

The best model of the \([\text{O III}] \lambda \lambda 4958,5007 \text{Å} \) doublet (which will be called ‘[\text{O III}] model’) was chosen based on \( \chi^2 \) statistics and residual minimization. The \([\text{O III}] \) model, shown in Fig. 6.2 superposed on the observed lines, includes four components:
• A narrow redshifted component (1N) with FWHM$_{1N}$=128±5 km s$^{-1}$ and velocity shift $v_{1N}$=99±35 km s$^{-1}$

• A narrow blueshifted component (2N) with FWHM$_{2N}$=104±4 km s$^{-1}$ and velocity shift $v_{2N}$=−80±35 km s$^{-1}$

• An intermediate component (I) with FWHM$_{I}$=709±75 km s$^{-1}$ and velocity shift $v_{I}$=25±38 km s$^{-1}$

• A very broad blueshifted component (VB) with FWHM$_{VB}$=2035±207 km s$^{-1}$ and velocity shift $v_{VB}$=−302±112 km s$^{-1}$

Velocity shifts were calculated with respect to the systemic velocity of the galaxy (i.e. derived from our redshift estimate), and the FWHM of each component is the intrinsic FWHM, taking into account the instrumental spectral resolution.

We derived a model for the permitted hydrogen emission lines using the H$\beta$ line. Interestingly, the best model for the H$\beta$ line was consistent with the [O III] model but required an additional redshifted component with $v$ = 398±171 km s$^{-1}$ and FWHM= 1969±662 km s$^{-1}$. The ‘H$\beta$ model’ is shown in Fig. 6.3 superposed on the observed spectrum. Nevertheless, this additional component was hard to detect in the other Hydrogen emission lines in the nuclear spectrum, mainly due to their weakness (e.g. Pa$\alpha$) or to the fact that they blend with other emission lines (e.g. H$\alpha$ and H$\gamma$). A possible explanation is that this component is due to light from the central broad line regions of the AGN scattered by an outflowing dusty medium, which can explain the redshift of the component (see e.g. di Serego Alighieri et al. 1995; Cimatti et al. 1997; Villar-Martín et al. 2000).

We found that the [O III] model provides a good fit for the [O II]λλ3726,29Å, the [O II]λλ7319,30Å$^1$ the [S II]λλ4069,76Å + H$\delta$, the [S II]λλ6717,31Å, the [N II]λλ6548,84Å + H$\alpha$, the [OI]λλ6300,63Å, the [S III]λλ9531Å and the Pa$\alpha$ lines. The line fluxes of the four components of each emission line are reported in Table 6.3 in Appendix 6.A.

As already reported by Holt et al. (2008) and Roche et al. (2016) the line profile of the [OI]λλ6300Å line shows a redshifted wing and is different from the rest of the forbidden emission line profiles. Using the

$^1$This is actually a blend of the four [O II] lines at 7319, 7320, 7330, 7331 Å and was fitted as a doublet assuming the line centers to be at 7320.1Å and 7330.2Å (based on Sivjee et al. 1979).
Figure 6.2 – The [O III]λλ4958,5007Å doublet (black solid line) and the [O III] model (red solid line). The [O III] model includes: two narrow components (1N and 2N component, green dotted line), one intermediate component (I component, yellow dot-dashed line) and one really broad component (VB component, blue dashed line). The residuals of the fit are normalized and plotted below the spectrum (black dot-dashed line). The vertical dashed lines marks the restframe wavelength of the emission lines. The inset in the top left part of the plot shows a zoom-in of the I and VB components.
Figure 6.3 – The H$\beta$ line (black solid line) and the H$\beta$ model (red solid line). The H$\beta$ model includes: the four components of the [O III] model (see Fig. 6.2 for a description) and an additional broad redshifted component (magenta dot-dot-dot-dashed line). The residuals of the fit are normalized and plotted below the spectrum (black dot-dashed line). The vertical dashed lines marks the restframe wavelength of the emission line.
bright near-IR [S\textsc{iii}]λ9531Å, we found that this is due to contamination by the [S\textsc{iii}]λ6312Å line and it is not an intrinsic feature of the [O\textsc{i}]λ6300Å profile. The [O\textsc{i}]λ6300Å line fluxes have been corrected for this when used in line ratio diagnostics (e.g. in Sec 6.6). Additional details on this and on the line fits are reported in Appendix 6.A.

In the NIR part of the nuclear spectrum of PKS B1934-63 we detected the [Fe\textsc{ii}]λ1.257\,µm and Pa\textbeta\ lines which will be used in Sec. 6.6 to study the gas ionization state. Likely due to a noisier spectrum and to the lack of continuum subtraction in the NIR band, for both these lines the [O\textsc{iii}] model did not give a reliable fit. We fitted the [Fe\textsc{ii}]λ1.257 \,µm line using a single Gaussian function with velocity $v = -95\pm49 \,\text{km s}^{-1}$ and FWHM= 547±72 \,\text{km s}^{-1}. The Pa\textbeta\ line is double peaked and the best fitting model included the two narrow components of the [O\textsc{iii}] model and a third, broader, component centered at $v = -233\pm35 \,\text{km s}^{-1}$ and with FWHM= 900±193 \,\text{km s}^{-1}.

### 6.3.3 The density diagnostic diagram

One of our main goals was to derive a robust estimate of the electron density of the warm ionized gas. Thanks to the large wavelength coverage of our observations, we could use the density diagnostic diagram introduced by Holt et al. (2011), based on transauroral emission lines, to estimate the electron density of the four different gas components (see Fig. 6.4). This diagram uses the [O\textsc{ii}] (3726+3729)/(7319+7330) and [S\textsc{ii}] (4069+4076)/(6717+6731) line ratios and provides also an estimate of the reddening of the gas. As already discussed in Holt et al. (2011) and Rose et al. (2018), compared to the classical line ratios, these diagnostics are sensitive to higher densities.

Fig. 6.4 shows where the four kinematical components of the warm ionized gas are situated in the diagnostic diagram. To derive values for the gas electron density, we have overplotted AGN photoionization models for different reddening factors.\footnote{The models were produced using the Cloudy (C13.04, Ferland et al. 2013) photoionization code and the Calzetti et al. (2000) reddening law. The models shown in Fig. 6.4 have solar metallicity, a photoionizing continuum with $\alpha = -1.5$ and a ionization parameter $U=0.005$, reproducing typical conditions of an AGN.}

Holt et al. (2011) showed that this density diagnostic diagram is not sensitive to the parameters of the AGN photoionization models. This
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Figure 6.4 – Density diagnostic diagram using the logarithm of the [OII] \((3727+3729)/(7318+7319+ 7330+7331)\) and of the [SII] \((4068+4076)/(6716+6731)\) line ratios. Each sequence of black squares, joined by the dashed black line, is a sequence of AGN photoionization models with constant power-law index \((\alpha = -1.5)\) and ionization parameter \((U = 0.005)\), created varying the electron density of the model in the interval \(n_e = 100 - 10^6\) cm\(^{-3}\) (from top-left to bottom-right) with a step \(\Delta \log_{10} n_e = 0.5\). The three different sequences in the plot (from top-right to bottom-left) are associated with \(E(B-V) = 0, 0.5\) and 1. Green circles represent the narrow components, the intermediate and very broad components are indicated by the gold and blue circle respectively. Error bars for each point are estimated as described in the text.

means that the location of the model points in the diagram does not change significantly when the spectral index \(\alpha\) of the AGN continuum power-law \((F_\nu \propto \nu^\alpha)\) and the ionization parameter \(U\) are varied.

From the density diagnostic diagram we extracted \(\log n_e(1N)\) cm\(^{-3}\) = 2.4 ± 0.45, \(\log n_e(2N)\) cm\(^{-3}\) = 2.7 ± 0.45 for the two narrow components, \(\log n_e(I)\) cm\(^{-3}\) = 4.6 ± 0.25 for the intermediate component, and \(\log n_e(VB)\) cm\(^{-3}\) = 5.5 ± 0.35 for the very broad component. The error bars were estimated summing in quadrature the statistical error from the fitting procedure and the uncertainty in the flux calibration. It is worth mentioning that the [SII]λ6717/λ6731 line ratio, classically used as
a density diagnostic, confirmed these results for the narrow components and the intermediate component. In fact, the $[\text{S} \text{II}] \lambda 6717/\lambda 6731$ ratio is $1.10 \pm 0.4$ and $1.03 \pm 0.04$ for the narrow components and goes down to $0.45 \pm 0.04$ for the intermediate component, indicating a density of about $3 \times 10^2 \text{ cm}^{-3}$ and higher then $10^4 \text{ cm}^{-3}$ respectively. Due to a lower S/N, we could not estimate the density in this way for the very broad component.

The density diagnostic diagram shows that the warm ionized gas is spanning a significant range of densities going from $\sim 3 \times 10^2 \text{ cm}^{-3}$ up to $10^5 \text{ cm}^{-3}$, with the higher values found for the broader components.

The comparison between the observed points and the sequences of models with different $E(B-V)$ values in the density diagnostic diagram allowed us to derive estimates of the reddening of the four kinematical components for the warm ionized gas. We found $E(B-V)_{1N} = 0.52 \pm 0.12$, $E(B-V)_{2N} = 0.40 \pm 0.12$ for the narrow components, $E(B-V)_I = 0.05 \pm 0.20$ for the intermediate component and $E(B-V)_{VB} = 0.12 \pm 0.25$ for the very broad component.

We could compare these numbers to the reddenings estimated using the classical approach of the hydrogen line ratios (i.e. the Balmer decrement). We used the $\text{H} \alpha/\text{H} \beta$ and the $\text{Pa} \alpha/\text{H} \beta$ line ratios and we converted them to a color excess $E(B-V)$ following the approach of Momcheva et al. (2013) and using the Calzetti et al. (2000) extinction curve. The errors on the line ratios take into account both the statistical error of the fitting procedure and the uncertainty in the flux calibration. From the $\text{H} \alpha/\text{H} \beta$ line ratio we obtained $E(B-V)_{1N} = 0.43 \pm 0.135$, $E(B-V)_{2N} = 0.40 \pm 0.135$, $E(B-V)_I = 0.56 \pm 0.137$ and $E(B-V)_{VB} = 0.186 \pm 0.8$. From the $\text{Pa} \alpha/\text{H} \beta$ line ratio we obtained $E(B-V)_{1N} = 0.28 \pm 0.11$, $E(B-V)_{2N} = 0.25 \pm 0.11$, $E(B-V)_I = 0.11 \pm 0.19$ and $E(B-V)_{VB} = 0.82 \pm 0.85$. Taking into account the uncertainties, there is general good agreement between these values and the $E(B-V)$ values extracted from trans-auroral lines. The large uncertainties of the classical approach are mainly due to the faintness of the $\text{Pa} \alpha$ line (e.g. the difficulty in determining its continuum level) and the complex line blend in which the $\text{H} \alpha$ line is included. We thus preferred to adopt the reddening values coming from the density diagnostic diagram, which are based on the strong emission lines. These values are reported in Table 6.1 and will be used in the estimate of the intrinsic $[\text{O} \text{III}]$ and $\text{H} \beta$ luminosities of the different gas components.

We found that none of the kinematic components shows high reddening and that the reddening of the intermediate and very broad components is
lower than those of the narrow components. This is consistent with the results for some ultraluminous infrared galaxy (ULIRG) in the sample of Rose et al. (2018) but at odds with the results on the compact radio source PKS B1345+12 obtained by Holt et al. (2011) who, with the same method, found higher reddenings for broader components.

### 6.3.4 The radius of the narrow and broad gas components

To understand whether the warm ionized gas is extended or concentrated in the central regions of the host galaxy we used the \([\text{O} \text{III}]\)\(\lambda5007\) Å line and the spatial information contained in the slit spectrum.

We extracted spatial profiles for the warm ionized gas components (i.e. one for the two narrow components and one including the intermediate and the very broad components) and compared them to the seeing of our observations. To extract these profiles, we collapsed the slit spectrum along the spectral direction over a given velocity range (with respect to the systemic velocity). The selected velocity range for the narrow components was \(-226 \lesssim v \lesssim 279\) km s\(^{-1}\). For the intermediate and very broad component we took the velocity range \(-854 \lesssim v \lesssim -348\) km s\(^{-1}\). The profile of the galaxy starlight emission was extracted using two windows, one on the red side \((-2031 \lesssim v \lesssim -3044\) km s\(^{-1}\)) and one on the blue side \((-5867 \lesssim v \lesssim -4855\) km s\(^{-1}\)) of the \([\text{O} \text{III}]\)\(\lambda\lambda4958,5007\) Å lines.

The host galaxy profile was then corrected for the differences in the widths of the slices and subtracted from the ionized gas profiles, the residual were then fitted with a Gaussian function. For both these profiles we obtained a FWHM of 0.95±0.01 arcsec, which is consistent with the FWHM of the seeing (i.e. 0.97±0.06 arcsec, see Sec. 6.2). This indicates that the warm ionized gas (of all the kinematical components) is not spatially resolved by our observations using this technique and is concentrated in the nuclear regions of the host galaxy.

To obtain an upper limit on the radius of the warm ionized gas we used the following equation:

\[
r \leq \frac{1}{2} \sqrt{(\text{FWHM} + 3\sigma)^2 - \text{FWHM}^2}
\]

(6.1)

where FWHM is the seeing and \(\sigma\) is the uncertainty on the seeing. We obtained \(r \leq 0.3\) arcsec that, at the redshift of the galaxy, is equivalent to \(r \leq 955\) pc.
<table>
<thead>
<tr>
<th></th>
<th>1N Component</th>
<th>2N Component</th>
<th>I Component</th>
<th>VB Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v$ [km s$^{-1}$]</td>
<td>99.6±35.4</td>
<td>−80±35.4</td>
<td>25±38.5</td>
<td>−302±112</td>
</tr>
<tr>
<td>FWHM [km s$^{-1}$]</td>
<td>128±5.3</td>
<td>104±4.2</td>
<td>709±75.3</td>
<td>2035±207</td>
</tr>
<tr>
<td>log $n_e$ [cm$^{-3}$]</td>
<td>2.4 ± 0.45</td>
<td>2.7 ± 0.45</td>
<td>4.6 ± 0.25</td>
<td>5.5 ± 0.35</td>
</tr>
<tr>
<td>$E(B−V)$</td>
<td>0.52±0.125</td>
<td>0.4±0.125</td>
<td>0.05±0.2</td>
<td>0.125±0.25</td>
</tr>
<tr>
<td>$L$(H$\beta$) [erg s$^{-1}$]</td>
<td>$(1.89±0.20) \times 10^{41}$</td>
<td>$(1.25±0.12) \times 10^{41}$</td>
<td>$(6.93±0.70) \times 10^{40}$</td>
<td>$(2.67±0.26) \times 10^{40}$</td>
</tr>
<tr>
<td>$M_{\text{gas}}$ [M$_\odot$]</td>
<td>$(5.1±0.5) \times 10^{6}$</td>
<td>$(1.7±0.2) \times 10^{6}$</td>
<td>$(1.2±0.1) \times 10^{4}$</td>
<td>$(5.7±0.5) \times 10^{2}$</td>
</tr>
</tbody>
</table>

Table 6.1 – In the table we report the kinematical and physical properties of the four kinematical components found for the warm ionized gas. The central velocity $v$ and FWHM are obtained from the [O III] model, the electron density $n_e$ and reddening $E(B-V)$ values are extracted using the density diagnostic diagram in Sec. 6.3.3, $L(H\beta)$ is the reddening corrected H\beta luminosity and $M_{\text{gas}}$ is the mass of warm ionized gas estimated in Sec. 6.5.
6.4 Gas kinematics in the inner regions

Using the spectro-astrometry technique we could study the spatial extents of the different ionized gas components, overcoming the limitations given by the seeing. Spectro-astrometry uses high-S/N long-slit spectra to measure the centroid position of an unresolved object as function of wavelength. It is based on the fact that the centroid position can be measured with much higher precision than the seeing-limited spatial resolution of the observations (Bailey 1998b), and has been used to identify and study binary stars (see Bailey 1998a; Takami et al. 2003).

We could use this technique on the high S/N [O\textsc{iii}] λ5007Å line in our slit spectrum and investigate how the warm ionized gas at different velocities is distributed along the slit in the spatial direction. In this way, we could probe the gas distribution at subarcsec scales, which at the redshift of PKS B1934-63 correspond to scales of tens of parsec. In the slit spectrum, we isolated the region around the [O\textsc{iii}] λ5007Å line and for a given pixel along the spectral direction we extracted a profile of the ionized gas along the spatial direction. Every spatial profile probes warm ionized gas at a different velocity. Then, we fitted each extracted spatial profile with a Gaussian function and used the fitted profile center to establish the spatial location of the gas at that specific velocity.

We used an average spatial profile of the galaxy starlight to locate the host galaxy center and we took this as a reference point to establish the location of the ionized gas. We also subtracted the starlight spatial profile from the ionized gas spatial profiles to avoid contamination from the light of the host galaxy. This was particularly important for the profiles extracted at velocities $v < -250$ km s$^{-1}$ and $v > 250$ km s$^{-1}$, where the fainter [O\textsc{iii}] λ5007Å emission of the broad (i.e. the intermediate and very broad) components of the warm ionized gas is located. To increase the S/N of the gas spatial profiles at these velocities we binned the data along the spectral direction using a box which is 3 pixels wide. Instead, for gas at velocities $-250 < v < 250$ km s$^{-1}$ we extracted a spatial profile for every pixel along the spectral direction.

In Fig. 6.5 we show the spatial position of the fitted centers of the gas spatial profiles (expressed in arcsec/pc) as a function of the velocity associated with each profile. The zero point along the x axis is the systemic velocity of the galaxy, while the zero point along the y axis is the fitted center of the galaxy spatial profile.
6.4. Gas kinematics in the inner regions

Figure 6.5 – Fitted centers of the [O III]5007Å emission line spatial profiles, measured in arcsec (left y axis) and parsec (right y axis), as function of velocity. The black dashed vertical and horizontal lines marks the zero point of both axes. The blue dashed lines mark the error weighted mean position of the [O III] spatial profiles at $v < 250 \text{ km s}^{-1}$ and at $v > 250 \text{ km s}^{-1}$ while the red solid line marks their average. The negative values along the y axis indicate the direction pointing toward the companion galaxy.
The S-shaped trend we see in Fig. 6.5 for the two narrow components (i.e. at $-250 < v < 250$ km s$^{-1}$) might be explained by a disk-like structure or a bi-conical outflow in the central regions of the galaxy (up to about $\pm 200$ pc). The curve is symmetric around the zero velocity value and reaches a maximum spatial shift at about $\pm 150$ km s$^{-1}$. The overall curve is clearly spatially shifted with respect to the zero point along the y axis (i.e. the center of the galaxy), and this might be explained by the effect of obscuring dust, which can potentially shift the position of the galaxy spatial profile peak that we are using as an indicator of the true AGN nucleus position.

Unlike Roche et al. (2016), we do not find evidence for gas emission on large scales (>1 kpc). However, if the inner structure we detect from spectro-astrometry is a circum-nuclear disk (CND), it would rotate in the same direction as the more extended gas disk seen by Roche et al. (2016). The fact that our slit is not aligned with the major axis of the structure that Roche et al. (2016) observe may explain why this is, instead, spatially unresolved by our observations, as shown in Sec. 6.3.4. The existence of CND of warm and cold gas, extended on scales of few hundreds of pc, at the center of AGN has already been found in Chapter 5 and by the studies of, for example, Dumas et al. (2007); Hicks et al. (2013) and García-Burillo et al. (2016), and it has been proposed that these structures constitute the reservoir of gas from which the SMBH feeds.

It is worth noting that the amplitude of the rotation that we find is larger than in Roche et al. (2016). This is possibly due to the fact that their observations do not resolve the double peak of the [O III]$\lambda$5007Å line and they used a single Gaussian fit to derive the [O III]$\lambda$5007Å velocity field, smoothing out the velocity gradient that we observe.

On the other hand the gas at $v < -250$ km s$^{-1}$ and at $v > 250$ km s$^{-1}$ is associated with the intermediate and the very broad components and is representative of the warm ionized gas that is outflowing. The error weighted mean positions of the gas at $v < -250$ km s$^{-1}$ and at $v > 250$ km s$^{-1}$ are $-0.047 \pm 0.002$ and $-0.085 \pm 0.003$ respectively (see Fig. 6.5). This spatial asymmetry supports the idea that the geometry of the outflowing gas is bi-conical. Assuming a bi-conical geometry (i.e. the blueshifted and redshifted gas emission comes from the two sides of the nucleus) we can estimate the position of the nucleus (i.e. red horizontal line in Fig. 6.5) and get an idea of the radius of the outflowing gas. In this way we find that the outflow has a radius of 59$\pm$12 pc. This matches
with the radial extent of the radio source well (the separation between the radio lobes of PKS B1934-63 is 131.7±0.9 pc) and suggests that the warm ionized gas is outflowing as a consequence of the interaction with the radio jets. We are aware of the fact that taking only the average position for the gas in the broad wings of the [O III]λ5007Å line might underestimate the size of the outflow. However, even considering the higher absolute value for the shift of the gas at $v < -200$ km s$^{-1}$ and at $v > 200$ km s$^{-1}$ with respect to the estimated position of the nucleus, we find that, including the errors on the spatial shifts, the outflow would have a maximum radius of $\sim 175$ pc. This indicates that the outflow is extended on spatial scales that are comparable with the size of the radio source.

6.5 Warm ionized gas and parameters of the outflow

We estimated the warm ionized gas mass of the different kinematical components using the following equation:

$$M_{\text{gas}} = \frac{L(\text{H}\beta)m_p}{n_e \alpha_{\text{H}\beta}^\text{eff} h \nu_{\text{H}\beta}}$$

where $L(\text{H}\beta)$ is the H\beta luminosity corrected for dust extinction, $m_p$ is the proton mass, $n_e$ is the electron density from the density diagnostic diagram, $\alpha_{\text{H}\beta}^\text{eff}$ is the effective H\beta recombination coefficient (taken as $3.03 \times 10^{-14}$ cm$^3$s$^{-1}$ for case B in the low density limit; Osterbrock & Ferland 2006), $\nu_{\text{H}\beta}$ is the frequency of the H\beta, and $h$ is the Planck constant.

The $L(\text{H}\beta)$ and the estimated $M_{\text{gas}}$ of each kinematical component are reported in Table 6.1.

We found that the two narrow components have a mass of warm ionized gas of $M_{\text{gas}}(1\text{N}) = (5.1 \pm 0.5) \times 10^6$ M$_{\odot}$ and $M_{\text{gas}}(2\text{N}) = (1.7 \pm 0.2) \times 10^6$ M$_{\odot}$. The intermediate component has a gas mass of $M_{\text{gas}}(\text{I}) = (1.2 \pm 0.1) \times 10^4$ M$_{\odot}$, while for the very broad component we found $M_{\text{gas}}(\text{VB}) = (5.7 \pm 0.5) \times 10^2$ M$_{\odot}$. It is clear that almost the entire reservoir of the host galaxy’s warm ionized gas is found in the two narrow components; the intermediate and the very broad components represent only a small fraction of the warm ionized gas reservoir.

With a reliable estimate of the electron density of the outflowing warm ionized gas we could characterize the properties of the outflow. Following
the method described in Sec. 4.1 of [Rose et al. (2018)] we determined the mass outflow rate \( \dot{M} \), the outflow kinetic power \( \dot{E} \) and efficiency \( F_{\text{kin}} = \dot{E}/L_{\text{bol}} \) using the following formulae:

\[
\dot{M} = \frac{L(H\beta) m_p v_{\text{out}}}{n_e \alpha_{\text{H}\beta}^\text{eff} h \nu_{H\beta} r}
\]  

(6.3)

\[
\dot{E} = \frac{\dot{M}}{2} (v_{\text{out}}^2 + 3\sigma^2)
\]  

(6.4)

where \( v_{\text{out}} \) is the velocity, \( r \) is the radius and \( \sigma \) is the line-of-sight velocity dispersion (\( \sigma = \text{FWHM}/2.355 \)) of the outflow.

To estimate these parameters we used the radii estimated in Sec. 6.3.4 (i.e. \( r < 955 \text{ pc} \)) and in Sec. 6.4 (i.e. \( r > 60 \text{ pc} \)) as upper and lower limits for the radius of the outflow respectively. We extracted the bolometric luminosity using the de-reddened \([\text{O} III] \lambda 5007\text{Å} \) total luminosity which is usually considered a good indicator of the AGN power (see [Heckman et al. 2004]). Summing the intrinsic \([\text{O} III] \lambda 5007\text{Å} \) luminosities of each component we obtained \( L_{[\text{O} III]} = (4.4 \pm 0.4) \times 10^{42} \text{ erg s}^{-1} \). To extract the bolometric luminosity we used the bolometric correction of [Lamastra et al. 2009], \( L_{\text{bol}} = 454 L_{[\text{O} III]} \) valid for object with intrinsic \([\text{O} III] \lambda 5007\text{Å} \) luminosity in the interval \( L_{[\text{O} III]} = 10^{42-44} \text{ erg s}^{-1} \). This resulted in a bolometric luminosity of \( L_{\text{bol}} = (2 \pm 0.2) \times 10^{45} \text{ erg s}^{-1} \) which makes PKS B1934-63 a type II quasar according to the criterion of [Zakamska et al. 2003].

We estimated the outflow properties for the gas emitting the very broad component and for both of the broader components together (i.e. the intermediate and very broad component). In the latter case, for \( L(H\beta) \) we took the intrinsic integrated \( H\beta \) luminosity of the two components, while for the \( n_e \), the \( v_{\text{out}} \) and the FWHM of the gas we took a flux weighted value. All the relevant quantities for these calculations are reported in Table 6.2 together with the estimated \( \dot{M} \), \( \dot{E} \), and \( F_{\text{kin}} \). In this way we obtained mass outflow rates in the range \( 10^{-3}-10^{-4} \text{ M}_\odot \text{ yr}^{-1} \) and outflow efficiencies in the range \( 10^{-4}-10^{-5} \%).

This approach assumed that the central velocity of the line associated with the outflowing gas is the true velocity of the outflow \( v_{\text{out}} \) and its broadening is due to the gas turbulence. A less conservative approach, which can potentially take into account projection effects, considers that
the broadening of the lines is due to the different projections of the velocity vectors of the gas in a quasi-spherical outflow. In this case the actual outflow velocity \( v_{\text{out}} \) is the maximum velocity that the gas reaches in the wings of the emission line profile. To estimate the maximum velocity of the gas we followed the approach of Rose et al. (2018) and took the velocity corresponding to a 5% cut of the flux in the blueshifted direction. Also in this case we report all the relevant quantities for the calculations and the estimated \( \dot{M}, \dot{E}, \text{and } F_{\text{kin}} \) in Table 6.2. With this method we obtained mass outflow rates and outflow efficiencies, for the intermediate and very broad components, which are, on average, one order of magnitude higher compared to the results obtained with the first approach.

Both methods gave outflow efficiencies that are among the lowest found for warm ionized gas outflows (see Fig.2 in Harrison et al. 2018). Our values are far from the 5-10% required by the classical AGN feedback models (e.g. Fabian 1999, Di Matteo et al. 2005, Springel et al. 2005) and also lower that the 0.5% of the multi-staged model proposed by Hopkins & Elvis (2010). However, as stressed by Harrison et al. (2018), there are some caveats to consider when comparing the AGN feedback efficiency derived from observations to the prescription of cosmological models, especially due to the fact that the energy that is actually transferred to the warm and cool ISM can be a fraction of the energy injected by the AGN into the surrounding medium.

### 6.6 Gas excitation

Given that the gas in the intermediate and the very broad components shows remarkable differences in terms of densities and kinematics from the rest of the warm ionized gas, we investigated whether these components also stand out in terms of their ionization properties.

In Fig. 6.6 and Fig. 6.7 we present the classical BPT diagrams originally introduced by Baldwin et al. (1981) with the observed line ratios of the different gas kinematical components. As expected, the observed line ratios of the four kinematical components are typical of AGN, although with some differences between the components. As in the case of the density diagnostic diagram, the two narrow components have similar line ratios (see Fig. 6.6), confirming that they are part of the same structure.
Table 6.2 - In the table we report the mass outflow rates $\dot{M}$, the outflow kinetic energy $\dot{E}$ and efficiency $F_{\text{kin}} = \dot{E}/L_{\text{bol}}$ obtained with the two different methods described in the text, together with all the relevant quantities used in the calculation. Column 2 and 3 report the values obtained using the central velocity of the outflowing gas as $v_{\text{out}}$, while the column 4 and 5 report the values obtained using the maximum velocity $v_{\text{max}}$ as $v_{\text{out}}$. 
All the gas components, but in particular the very broad component, have high values of the [O\textsc{i}]\,λ6300/H\textsc{α} line ratio, higher than those usually measured in AGN, and which are indicative of shock-ionized gas. In fact, the [O\textsc{i}]\,λ6300Å line is emitted by warm weakly ionized gas typically located in the transition region between ionized gas and neutral gas. Only high energy photons can penetrate this region stimulating the [O\textsc{i}]\,λ6300Å emission, and a source of such high energy photons can be the AGN continuum radiation, shocks or a combination of the two.

We investigated the gas ionization mechanisms by comparing the observed line ratios with model grids of AGN photoionization and of shocks. The model grids were taken from the ITERA tool (Groves & Allen 2010) and created using MAPPINGS III (Sutherland et al. 2013). The AGN photoionization model grids (see Fig. 6.6 and upper panel in Fig. 6.7) were obtained by varying the spectral index $\alpha$ from $-2$ to $-1.2$ and the ionization parameter $\log U$ from $-4$ to $0$. The shock models (see lower panel in Fig. 6.7) have solar metallicity, cover shock velocities in the range $v_s=100$-1000 km\,s$^{-1}$ and magnetic fields (i.e. pre-shock transverse magnetic field) in the range $B=0.01$-1000 $\mu$G.

In Fig. 6.6 we compare the line ratios of the narrow components to AGN photoionization models with gas density $n_e = 10^3$ cm$^{-3}$ (according to the densities derived in Sec. 6.3.3) and both solar and twice solar (i.e. 2 $Z_\odot$) metallicity. The comparison of the line ratios with the photoionization models provides good evidence for super-solar metallicities in the near-nuclear regions. We also found a good consistency between the positions of the points and the models (in $U$ and $\alpha$) in all three plots for twice solar metallicity. The narrow components do not show kinematical evidence of shocked gas (i.e. large line width) and, for this reason, we did not compare their line ratios with shock models. It is possible that the gas of the narrow components is part of the shock precursor. However, for solar metallicities, precursor models have line ratios similar to the AGN photoionization models and would also fail to explain the observed line ratios. We cannot comment on precursor models with metallicities higher than solar because of the lack of such models.

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3The shock models included in the ITERA tool were taken from Allen et al. (2008).
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Figure 6.6 – BPT diagrams for the two narrow components with models of AGN photoionization with solar metallicity (upper panels) and twice the solar metallicity (lower panels). Models have gas density $n_e = 10^3 \text{cm}^{-3}$, dashed lines indicates models with constant photoionization parameter $\log U$ (going from $-4$ to 0, from bottom to top), while solid lines refer to models with constant spectral index $\alpha$ (going from $-2$ to $-1.2$, from left to right). The solid line in all the panels is the Kewley et al. (2001) maximum starburst line. The dashed line in the left panels is the semi-empirical Kauffmann et al. (2003) line. The dashed line in the central and right panels is the empirical Kewley et al. (2006) line separating Seyfert from LINERS.
Figure 6.7 – BPT diagrams for the intermediate and very broad components with models of AGN photoionization (upper panels) and shocks (lower panels) with solar metallicity. The AGN photoionization models have gas density $n_e = 10^5\text{cm}^{-3}$, $\alpha$ and $\log U$ parameters vary in the same range as described in Fig. 6.6. The shock models have pre-shock gas density of $n_e = 10^3\text{cm}^{-3}$, dashed lines indicate models with constant shock velocity $v_s$ (ranging in the interval 100-1000 km s$^{-1}$, from left to right) while solid lines refer to models with constant magnetic parameter $B$ (ranging in the interval 0.01-1000 $\mu$G, from bottom to top). The solid and dashed black lines are the same as in Fig. 6.6.
In Fig. 6.7 we use both AGN photoionization and shock models to study the ionization state of the gas in the intermediate and the very broad components. We considered AGN photoionization models\(^4\) with a gas electron density \(n_e = 10^5 \text{ cm}^{-3}\), while for the shock models we assumed a shock compression factor of 100 and took a pre-shock gas electron density of \(n_e = 10^3 \text{ cm}^{-3}\). The assumed compression factor was intended to take into account the fact that while shock conditions cause a modest density jump (maximum factor \(\sim 5\), see Fig. 7 in Sutherland & Dopita 2017), the temperature jump will further increase the pressure and thus the compression of the gas in the post-shock regions. We found that, overall, the shock models reproduce better than the AGN photoionization models the observed line ratios in the three BPT diagrams (see Fig. 6.7). In particular, the \([\text{SII}]\lambda\lambda6717,31/\text{H}\alpha\) and the \([\text{OI}]\lambda6300/\text{H}\alpha\) line ratios of the intermediate component can be explained by shock models with velocities \(v_s=400-500 \text{ km s}^{-1}\).

The line ratios of the very broad component were more difficult to explain with current models. The outflowing gas of the very broad component stands out from the rest of the warm ionized gas in terms of both the \([\text{NII}]\lambda6584/\text{H}\alpha\) and the \([\text{OI}]\lambda6300/\text{H}\alpha\) line ratios but not in terms of the \([\text{SII}]\lambda\lambda6717,31/\text{H}\alpha\) ratio. This is explainable with the high densities which are associated with this gas component and with the fact that the \([\text{SII}]\) lines have a lower critical density (about \(5\times10^3 \text{ cm}^{-3}\), Zheng 1988) than the \([\text{NII}]\) and \([\text{OI}]\) emission lines. Considering the trend of the model grids, the \([\text{OI}]\lambda6300/\text{H}\alpha\) line ratio is consistent with shocks of higher velocities (\(v_s \geq 1000 \text{ km s}^{-1}\)) as also suggested by the extreme kinematics of the gas of the very broad component. On the other hand, the high value of the \([\text{NII}]\lambda6584/\text{H}\alpha\) line ratio might be an indication of and enhanced N/O ratio (i.e. higher than solar) for the gas of the very broad component (see e.g. Tadhunter et al. 1994a; Matsuoka et al. 2017).

We are aware that the variation in the shock compression factor and gas metallicity plays a role in the final line ratios of the models. In addition, degeneracies in the fitting of the intermediate and very broad components in the \([\text{NII}] + \text{H}\alpha\) blend may contribute to the extreme \([\text{OI}]/\text{H}\alpha\) and \([\text{NII}]/\text{H}\alpha\) ratios that are observed. New shock models with a fully-self consistent treatment of the pre-shock ionization and thermal structure are

\(^4\)This model grid was not included in the ITERA tool and is produced using Cloudy (C13.04, Ferland et al. 2013) photoionization code
being developed for fast shocks and high gas electron densities (Sutherland & Dopita 2017).

Additional evidence for shocks is also provided by the \([\text{Fe II}]\lambda 1.257\mu m/\text{Pa}\beta\) line ratio. This line ratio can indicate whether shock ionization is producing the \([\text{Fe II}]\) emission. This was first suggested by Forbes & Ward (1993) and Blietz et al. (1994) who found a correlation between the \([\text{Fe II}]\) and the radio emission in radio AGN. It has been shown that in galaxies hosting an AGN a \([\text{Fe II}]\lambda 1.257\mu m/\text{Pa}\beta\) ratio close to 0.6 is produced by AGN photoionization, while a ratio close to 2 is related to shock excitation (Storchi-Bergmann et al. 1999; Rodríguez-Ardila et al. 2004).

In the NIR band of the nuclear spectrum of PKS B1934-63 we detected both the \([\text{Fe II}]\lambda 1.257\mu m\) and \(\text{Pa}\beta\) lines. Due to their low S/N, we could not fit the lines with the \([\text{O III}]\) model (see Fig. 6.21) and we extracted a line ratio using the total flux of the two lines. We find a \([\text{Fe II}]1.257/\text{Pa}\beta=1.44\pm0.2\) which is indicative of shock-ionized gas.

### 6.7 The H$_2$ warm molecular and the neutral gas

Compact steep-spectrum radio sources are known to host massive outflows of molecular and atomic gas (see e.g. Morganti et al. 2005a; Dasyra & Combes 2012; Tadhunter et al. 2014). Probing only the warm ionized gas phase, we might be missing part of the gas that is outflowing. Thanks to the large wavelength range covered by X-shooter we could probe the kinematics of the warm molecular gas via the H$_2$ emission lines detected in the NIR band. In the nuclear spectrum of PKS B1934-63 we identified the H$_2$ S(5)1-0 line at 1.835 \(\mu m\), the H$_2$ S(4)1-0 line at 1.891 \(\mu m\), and the H$_2$ S(3)1-0 line at 1.957 \(\mu m\). From Fig. 6.8 it is already clear that H$_2$ emission lines are narrower compared to the warm ionized gas emission lines (e.g. the Pa$\alpha$ line).

To provide an overview of the kinematics of the different phases of the gas, in Fig. 6.9 we compared the kinematics of the warm ionized gas with the kinematics of the warm molecular and atomic gas by plotting together the normalized line profiles of the \([\text{O III}]\lambda 5007\AA\), the H$_2$ and the H I 21 cm spectral lines. The H$_2$ profile in Fig. 6.9 is the stacked profile of the H$_2$ 1.957 \(\mu m\) and H$_2$ 1.835 \(\mu m\) lines and appears slightly blueshifted with respect to the systemic velocity of the host galaxy. Its peak coincides with the the peak of the blueshifted narrow component of the ionized gas and does not show clear signs of kinematically disturbed gas, however, due to
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Figure 6.8 – Section of the nuclear spectrum of PKS1934-63 in the NIR band showing the warm molecular H$_2$ emission lines and the Pa$\alpha$ line. The wavelength and the name of each line are indicated.

The low S/N and the fluctuations of the continuum, we cannot completely rule out the presence of outflowing gas.

HI gas has been detected in absorption against the radio continuum source by Véron-Cetty et al. (2000) and is shown inverted to emission for easy comparison in Fig. 6.9. These observations are tracing only the kinematics of gas that is located, in projection, in front of the compact radio source. The HI has a velocity shift ($v=116$ km s$^{-1}$) which is comparable to the redshifted narrow component of the warm ionized gas and is characterized by a very narrow profile (FWHM=18.8 km s$^{-1}$). This indicates that it is possibly connected to infalling clouds of atomic gas located in front of the radio source (like in the case of PKS B1718-649, see Maccagni et al. 2014).

A more global view on the atomic gas phase of the ISM could be obtained by using the absorption lines of the [Na I D] doublet at $\lambda\lambda$5890,5896Å (see e.g. Lehner et al. 2011). After the stellar continuum of the host galaxy was subtracted, we did not find evidence for the [Na I D] absorption in the nuclear spectrum of PKS B1934-63. This is possibly due to the compactness of the neutral ISM, which is concentrated in the inner
regions of the galaxy (like the warm ionized gas) and does not absorb its diffuse starlight.

In the UVB part of the spectrum, we detected the ISM absorption features of the Mg\textsc{ii}$\lambda\lambda 2795, 2802$ Å doublet. These absorption lines trace ionized gas in the ISM that is in a low ionization state, and are superimposed on the Mg\textsc{ii} emission lines, at the same wavelengths, due to the AGN. Even though we fitted the Mg\textsc{ii} lines with a simple model, which might ignore the complex emission line profile underneath the absorption (see Fig. 6.12), we did not observe clear signs of kinematically disturbed gas in absorption. In fact, the Mg\textsc{ii} emission and absorption are fit by single Gaussian components with a FWHM $\sim 1250$ km s$^{-1}$ and $\sim 200$ km s$^{-1}$ respectively and the absorption component is centered at the systemic redshift of the galaxy (see Appendix 6.A for further details).

The fact that we detected such deep Mg\textsc{ii} absorption, implying a covering factor of the line-emitting gas close to 1, but no clear evidence for ISM absorption of the stellar continuum at the same wavelength (c.f. Ca\textsc{ii}, [Na I D]) provides further evidence that the emission lines are emitted by a region that is compact relative to the stellar body of the galaxy.

We concluded that, while we clearly detect an outflow of warm ionized gas, there is no strong evidence of cold outflowing gas traced by the H$_2$, H\textsc{i}, and Mg\textsc{ii} lines. This is in contrast with the compact steep-spectrum radio sources like IC 5063 (Tadhunter et al. 2014; Morganti et al. 2015, Oosterloo et al. 2017), PKS B1345+12 (Morganti et al. 2013; Dasyra & Combes 2012) and 3C 305 (Morganti et al. 2005a) in which ionized gas outflows have also been detected. In these sources the cold molecular (CO) and warm molecular (H$_2$) gas has been found to be the dominant outflowing phase in terms of mass.

In recent years, the scenario in which cold gas is formed in situ, within the material swept away by the AGN, has gained more acceptance and has also been invoked to explain the properties of the multi-phase outflow of compact steep-spectrum radio sources (Tadhunter et al. 2014; Morganti et al. 2015). According to the latter scenario, at first the AGN drives fast shocks into the ISM, ionizing the gas and heating it to high temperatures (higher than $10^6$ K). The post-shock gas then cools down, accumulating as atomic and, eventually, cold molecular gas at a later stage. This means that outflows of warm ionized gas should be detected in the early phase of an AGN-ISM interaction, and only when sufficient time has elapsed for a substantial amount of gas to cool would we expect to be able to detect the
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Figure 6.9 – Normalized [O III]λ5007Å line (solid black), stacked H\textsubscript{2} line (solid red) and H I line (solid blue) in the velocity space. Each line is normalized with respect to its maximum value. The zero velocity along the x axis is the systemic velocity of the galaxy as extracted in Sec. 6.3.1 and is marked with the black vertical dashed line. The H I line has been observed in absorption by Véron-Cetty et al. (2000) and is reproduced as an emission line using a Gaussian function and the parameters reported in the text.
6.7. The $\text{H}_2$ warm molecular and the neutral gas

cold molecular counterpart of these outflows (e.g. using CO lines). Recent simulations confirmed this scenario, finding that molecular gas starts to form around few $10^5$ yr from the start of the AGN-ISM interaction (Richings & Faucher-Giguere 2017).

We performed a first attempt to test this scenario by integrating our findings with the outflow properties reported in the literature for other young compact radio sources. Compact radio sources have radio ages between $10^2$ yr and $10^5$ yr (Murgia 2003; Giroletti & Polatidis 2009) and we use them to sample outflowing gas at different times. Excluding PKS B1934-63, our target, only few other compact young radio sources have both an estimated radio age and observations of their multi-phase ISM. It is worth mentioning that the sources we selected from the literature cover three orders of magnitudes in radio power and their outflows properties might be due to an intrinsically different kind of interaction between the ISM and the radio plasma.

PKS B1718-649 is a younger (kinematical age $\sim 10^2$ yr, Giroletti & Polatidis 2009) compact radio source compared to PKS B1934-63, showing hints of warm ionized outflowing gas (blueshifted wings in the forbidden emission lines, see the optical spectrum in Filippenko 1985). Multi-wavelength observations find that, like in the case of our target, for this source there is no evidence of outflowing gas in colder phases (atomic HI, warm molecular H$_2$, Chapter 5; cold molecular CO, Maccagni et al. 2018).

An older compact radio source that is able to probe a more evolved stage of the AGN-ISM interaction is 3C 305. It has an estimated radiative age of $1.5\times10^5$ yr (Murgia et al. 1999) and shows evidence of an outflow
in the warm and cold molecular gas (Guillard et al. 2012 and Guillard et al. in prep.), and in the atomic HI and warm ionized gas (Morganti et al. 2005a).

Finally, B2 0258+35 is among the oldest compact radio sources (radiative age $\leq 9\times10^5$ yr, Giroletti et al. 2005, $\leq 5\times10^5$ yr Brienza et al. in prep.). Cold molecular CO and atomic HI gas have been detected (Prandoni et al. 2007; Struve et al. 2010) and show signs of disturbed kinematics suggestive of outflowing gas (Murthy et al. in prep.), while there is no evidence of outflowing gas in the warm ionized phase (see the optical spectrum presented in Emonts 2006 and the public data from the CALIFA survey [5]).

The timeline presented in Fig. 6.10 summarizes all the information on these sources in the context of the scenario that we are testing. The properties of the outflowing gas for PKS B1934-63 and of the compact steep-spectrum radio galaxies mentioned above support the scenario in which cold molecular gas might form within the outflow material, due to cooling of shock heated gas. According to this scenario, PKS B1718-649 and PKS B1934-63 represent the earliest stages of the AGN-ISM interaction, when the outflowing gas is initially shock heated. This gas then starts to cool down in the post-shock region and can be detected as cold outflowing gas, like in the case of 3C 305. Finally, the radio galaxy B2 0258+35 might be representative of the the final phases of the AGN-ISM interaction, when all the outflowing gas has completely cooled down. Considering the small amount of mass that is outflowing in the case of PKS B1934-63, there is the possibility that most of the mass is currently in a hotter phase (e.g. gas at $10^7$ K emitting in the X-ray band).

We are aware that the radiative and kinematical age of a radio galaxy might differ, and that the radiative age indicates the age of the particles within the radio lobes rather than the real age of the source. However, the ages that we are using are the only available estimates, and it has been shown that the radiative age of 3C 305 is representative of the age of the radio source (Murgia et al. 1999).

The timeline in Fig. 6.10 includes also the two compact steep-spectrum radio sources PKS B1345+12 and IC 5063. These are two of the best examples of compact sources where extensive multi-wavelength studies found a multi-phase outflow (for PKS B1345+12 see Morganti et al. 2005b).

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6.8. Conclusions

Compact and young radio galaxies are pivotal for our understanding of the feedback effect that radio sources have on their host galaxies. PKS B1934-63 is a young (∼1.6×10^3 yr) radio source and, given its proximity (z=0.1824) and high radio power (P_{1.4GHz} = 10^{27.2} W Hz^-1), it is considered as an archetypal compact radio galaxy.

The nuclear spectrum of PKS B1934-63 shows double peaked gas emission lines that have broad wings indicating a complex kinematics for the warm ionized gas and the presence of outflowing gas. In fact, the kinematical features of the intermediate and the very broad components, needed to model the broad part of the emission line profiles, and in particular their line width (FWHM of about 700 and 2000 kms^-1 respectively) clearly reflect non-gravitational motions of gas which is connected to an AGN-driven outflow.

We find that about 6.8×10^6 M_☉ of warm ionized gas is concentrated in the inner 500 pc of the host galaxy and only a small fraction of this gas is actually outflowing. Most of the warm ionized gas is included in a structure that shows a smooth velocity gradient in the velocity-position diagram presented in Fig. 6.5. Considering the rotating disk of warm ionized gas found by Roche et al. (2016) on larger scales, we tend to favor the hypothesis that this structure is a circum-nuclear disk with a radius of about 200 pc, which might constitute part of the gas reservoir from which the SMBH is fed (similar to what has been found by e.g. Dumas et al. 2007, Hicks et al. 2013 and in Chapter 5).

The results of our spectro-astrometry study show that, assuming a biconical geometry for the outflow, the spatial extent of the broad wings of the [O III]λ5007Å line matches the diameter of the radio source (i.e. about 120 pc). This indicates that the outflow is likely driven by the expansion of the radio source’s jets, in line with what is commonly found in other
compact and young radio sources (see e.g. O’Dea et al. 2002; Holt et al. 2008; Tadhunter et al. 2014).

By using the density diagnostic diagram introduced by Holt et al. (2011) we find a clear correlation between the FWHM of a component and its electron density (see Fig. 6.4), in line with the findings of Holt et al. (2011) and Rose et al. (2018). The warm ionized gas associated with the broad components reaches remarkably high electron densities ($10^{4.5}$-$10^{5.5}$ cm$^{-3}$).

We attribute the broadening of the spectral lines to the interaction of the AGN with the ISM, and we argue that the FWHM-density relation that we find is mainly driven by the ability of the AGN-ISM interaction to compress, at different levels, the gas, and increase its density.

Estimating the gas densities with the transauroral line technique allows us to have a reliable estimate of the properties of the warm ionized gas that is outflowing. We obtain low mass outflow rates (i.e. highest values in the range $10^{-3}$-$10^{-1}$ M$_{\odot}$ yr$^{-1}$) and we find that only a small fraction of the available accretion power of the AGN is used to drive the outflow (i.e. maximum efficiency $F_{\text{kin}} \sim 10^{-3}\%$). This does not match the results of, for example, Fiore et al. (2017) who report higher average outflow efficiencies in their collection of ionized gas outflows (i.e. 0.16-0.3\%). However, the latter outflows lack a robust estimate of the gas density that is always taken to be $\leq 10^3$ cm$^{-3}$, based on classical line ratio diagnostics or assumptions. It is worth mentioning that by adopting such densities, which are at least two order of magnitudes lower compared to the values we find, we would obtain an outflow mass rate and an outflow efficiency compatible with the findings of Fiore et al. (2017). Instead, our results provide new evidence that AGN feedback happens at a low efficiency, and are much close to the values reported by Villar-Martín et al. (2016) for luminous type 2 AGN, and by Rose et al. (2018) who used the same technique as this chapter, on a sample of local ULIRG. This also highlights the importance of a fair comparison between the observed efficiencies and the cosmological models predictions (see Harrison et al. 2018, for a discussion).

By using the optical $[\text{S}\ II] \lambda \lambda 6717,31/\text{H} \alpha$ and the $[\text{O}\ I] \lambda 6300/\text{H} \alpha$ and the NIR $[\text{Fe}\ II] \lambda 1.257/\text{Pa} \beta$ line-ratio diagnostics we find that the AGN-ISM interaction is driving shocks within the ISM. In particular, the comparison between model grids and the observed optical line ratios in the BPT diagrams indicates that the broad components of the warm ionized gas are being ionized by fast shocks with velocities $v_s \geq 400$-$500$ km s$^{-1}$, possibly reaching few thousands km s$^{-1}$. These velocities are compatible with the
width of the broad components and suggest that shocks are a feasible mechanism to accelerate the warm ionized gas to high velocities.

By studying the Mg\textsc{II} absorption and the H\textsc{2} emission lines we find that the absorbing low-ionization ISM and warm molecular gas do not show signs of outflowing and/or kinematically disturbed gas. In addition, past HI observations of the nuclear region of the host galaxy did not find outflowing gas in the atomic phase (Vérón-Cetty et al. 2000). This is at odds with other compact, steep-spectrum radio sources that are known to host ionized gas outflows, which usually show massive cold gas outflows (Morganti et al. 2005a, Dasyra & Combes 2012, Morganti et al. 2013, Tadhunter et al. 2014, Morganti et al. 2015). By integrating our findings with information on other compact radio galaxies from the literature, we suggest that the lack of cold outflowing gas in PKS B1934-63 might be explained by the fact that the shock-ionized outflowing gas did not have enough time to cool down given the young age of the radio source and, thus, the fact that the AGN-ISM interaction occurred recently. It is also possible that a fraction of the outflowing gas is in a hotter phase (e.g. T\sim 10^7\text{K}) which is missed by our observations. Our results strengthen the hypothesis that, in general, during an AGN-ISM interaction the AGN drives shocks within the ISM, and cold gas is formed in situ within the outflowing material. New observations probing the cold molecular gas (i.e. CO) in PKS B1934-63 will be crucial for completing the picture on the presence and kinematics of the colder gas phase.

Our work shows how a systematic and detailed characterization of the multi-phase properties of the outflows in compact young radio galaxies offers the possibility to study the origin of cold gas within outflows and has the potential to shed light on the relevance of AGN feedback operated by jets on galactic scales.

Acknowledgements

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Appendix 6.A  Stellar population and line fitting

This appendix includes the results of the stellar population and emission lines modelling. In the following we describe in more detail the fitting procedure for some of the spectral lines.

In the case of the Mg\textsc{ii} $\lambda\lambda 2795,2802$ Å doublet, the ISM Mg\textsc{ii} absorption lines are superimposed to the emission lines due to the AGN light. For each line of the doublet we use a Gaussian function to model the AGN emission and a Gaussian function to model the ISM absorption (see Fig. 6.12). The separation between the two emission and absorption components is fixed according to the laboratory rest wavelengths of the doublet, in addition we fix their sigma to be the same. We find that the Mg\textsc{ii} emission is fit by a Gaussian with FWHM=$1245\pm 99$ km s$^{-1}$ and a velocity shift $v=-53 \pm 35$ km s$^{-1}$ while the absorption component has a FWHM=$200\pm 38$ km s$^{-1}$ and a velocity shift $v=14\pm 36$ km s$^{-1}$.

In the case of the [N\textsc{ii}] and [O\textsc{i}] lines we fix the [N\textsc{ii}]$\lambda 6584/\lambda 6548$ and the [O\textsc{i}]$\lambda 6300/\lambda 6363$ line ratios to be equal to 3 according to atomic physics (Osterbrock & Ferland 2006). The [O\textsc{ii}]$\lambda 7319/\lambda 7330$ line ratio is fixed to be 1.24 because it is found not to vary with density. The [O\textsc{ii}]$\lambda 3729/\lambda 3726$ and the [S\textsc{ii}]$\lambda 6717/\lambda 6731$ ratios are limited within their theoretical values at low and high densities (Osterbrock & Ferland 2006). We also limit the [S\textsc{ii}]$\lambda 4069/\lambda 4076$ ratio to be in the range 3.01-3.28 according to the calculation made by Rose et al. (2018) at different densities.

The [O\textsc{i}]$\lambda 6300$ Å line shows a different profile compared to all the other forbidden emission lines and this is possibly due to contamination coming from the [S\textsc{iii}]$\lambda 6312$ Å line. Considering the flux of the [S\textsc{iii}]$\lambda 9531$ Å emission line we can predict the minimum total flux and peak emission
expected for the \([\text{S} \text{III}] \lambda 6312\AA\) line. To do this we assume the lower value that the \([\text{S} \text{III}] \lambda 9531/6312\) line ratio reaches in the high temperature regime (see Osterbrock & Ferland [2006]). We find that we expect to detect the emission of the \([\text{S} \text{III}] \lambda 6312\AA\) line in the nuclear spectrum of PKS B1934-63. In fact, we predict that the \([\text{S} \text{III}] \lambda 6312\AA\) line should have a total flux higher than \(17.5 \times 10^{-17}\) erg s\(^{-1}\) cm\(^{-2}\) and a line peak (assuming the four kinematical components of the \([\text{O} \text{III}]\) model) greater than about \(3 \times 10^{-17}\) erg s\(^{-1}\) cm\(^{-2}\) \AA\(^{-1}\). For this reason, when fitting the \([\text{O} \text{I}] \lambda \lambda 6300-63\) \AA doublet we include also a \([\text{S} \text{III}] \lambda 6312\AA\) component that is well reproduced using only the intermediate component of the \([\text{O} \text{III}]\) model (see Fig. 6.18).

In the fit of the \([\text{O} \text{II}] \lambda \lambda 7319,30\) \AA we also introduce and additional Gaussian component to take into account the emission of the \([\text{O} \text{II}] \lambda 7381\AA\) emission in the red wing of the doublet. In the same way we take into account the emission of the H\(_2\) S(4)1-0 line in the fit of the Pa\(\alpha\) line profile.
Figure 6.11 – Nuclear spectrum (black solid line), best model (red solid line) for the continuum emission and residual (green points). The masked regions in correspondence of emission lines are indicated in blue. The observed spectrum is smoothed with a box of 3 Å.
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Table 6.3 – Table reporting the fluxes of the four kinematical components of each fitted line. The fluxes are in units of $10^{-17}$ erg s$^{-1}$ cm$^{-2}$. The first and second column indicates the emission line ID and rest frame wavelength respectively. The error on the reported fluxes is about 10%.
Figure 6.12 – The Mg II λ2795,2802 Å lines (black solid line) and best fit model (red solid line). Each line is fitted with one Gaussian component to take into account the emission (green dot-dashed line) and one Gaussian component to take into account the absorption (blue dashed line). The residuals of the fit are normalized and plotted below the spectrum (black dot-dashed line). The vertical dashed lines mark the restframe wavelength of the fitted emission lines.
Figure 6.13 – [O II]λ3726,29Å emission lines (black solid line) and best fit model (red solid line). Each line is modeled using the [O III] model, the 1N and 2N components are plotted together with the green dotted line, the I component is the gold dot-dashed line, the VB component is the blue dashed line. The residuals of the fit are normalized and plotted below the spectrum (black dot-dashed line). The vertical dashed lines mark the restframe wavelength of the fitted emission lines.
Figure 6.14 – [O II]λ\text{7319,30 Å} and [O II]λ\text{7381 Å} emission lines (black solid line) and best fit model (red solid line). Each line of the [O II]λ\text{7320-30 Å} doublet is modeled using the [O III] model, the 1N and 2N components are plotted together with the green dotted line, the I component is the gold dot-dashed line, the VB component is the blue dashed line. The [O II]λ\text{7381 Å} line is modeled with a single Gaussian function indicated by the magenta dot-dot-dot-dashed line. The residuals of the fit are normalized and plotted below the spectrum (black dot-dashed line). The vertical dashed lines mark the restframe wavelength of the fitted emission lines.
Figure 6.15 – $\text{[S II]} \lambda \lambda 4069,76$ Å and H$\delta$ emission lines (black solid line) and best fit model (red solid line). Each line is modeled using the [O III] model, the 1N and 2N components are plotted together with the green dotted line, the I component is the gold dot-dashed line, the VB component is the blue dashed line. The residuals of the fit are normalized and plotted below the spectrum (black dot-dashed line). The vertical dashed lines mark the restframe wavelength of the fitted emission lines.
Figure 6.16 – \([\text{S}\ II] \lambda 6717,31\text{Å} \) emission lines (black solid line) and best fit model (red solid line). Each line is modeled using the \([\text{O} \ III] \) model, the 1N and 2N components are plotted together with the green dotted line, the I component is the gold dot-dashed line, the VB component is the blue dashed line. The residuals of the fit are normalized and plotted below the spectrum (black dot-dashed line). The vertical dashed lines mark the restframe wavelength of the fitted emission lines.
Figure 6.17 – Hα and [NII]λ6548-84Å emission lines (black solid line) and best fit model (red solid line). Each line is modeled using the [OIII] model, the 1N and 2N components are plotted together with the green dotted line, the I component is the gold dot-dashed line, the VB component is the blue dashed line. The residuals of the fit are normalized and plotted below the spectrum (black dot-dashed line). The vertical dashed lines mark the restframe wavelength of the fitted emission lines.
Figure 6.18 – $[\text{O I}]\lambda 6300-63\text{Å}$ and $[\text{S III}]\lambda 6312\text{Å}$ emission lines (black solid line) and best fit model (red solid line). Each line of the $[\text{O I}]\lambda 6300-63\text{Å}$ doublet is modeled using the $[\text{O III}]$ model, the 1N and 2N components are plotted together with the green dotted line, the I component is the gold dot-dashed line, the VB component is the blue dashed line. The $[\text{S III}]\lambda 6312\text{Å}$ line is modeled with a single Gaussian function indicated by the magenta dot-dot-dot-dashed line. The residuals of the fit are normalized and plotted below the spectrum (black dot-dashed line). The vertical dashed lines mark the restframe wavelength of the fitted emission lines.
Figure 6.19 – Paα and H₂ S(4)1-0 emission lines (black solid line) and best fit model (red solid line). The Paα line is modeled using the [O III] model, the 1N and 2N components are plotted together with the green dotted line, the B component is the gold dot-dashed line, the VB component is the blue dashed line. The H₂ S(4)1-0 is modeled with a single Gaussian function indicated by the magenta dot-dot-dot-dashed line. The residuals of the fit are normalized and plotted below the spectrum (black dot-dashed line). The vertical dashed lines mark the restframe wavelength of the fitted emission lines.
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Figure 6.20 – [S\text{III}]λ9531Å emission line (black solid line) and best fit model (red solid line). The [S\text{III}]λ9531Å line is modeled using the [O\text{III}] model, the 1N and 2N components are plotted together with the green dotted line, the I component is the gold dot-dashed line, the VB component is the blue dashed line. The residuals of the fit are normalized and plotted below the spectrum (black dot-dashed line). The vertical dashed lines mark the restframe wavelength of the fitted emission line.

Figure 6.21 – Section of the nuclear spectrum of PKS B1934-63 showing the Fe\text{II} 1.257 μm (left panel) and the Pa\text{β} (right panel) emission lines (black solid line). The best model is shown with the red solid line. The residuals of the fit are normalized and plotted below the spectrum (black dot-dashed line). The vertical dashed lines mark the restframe wavelength of the emission line. For the Pa\text{β} the model includes: two narrow components (green dotted line) and a broad component (blue dashed line).
“How few people are now enjoying with me
the sublime spectacle that
the heavens spread out, in vain, for drowsy men.”
Francois Xavier De Maistre, Night voyage around my room.

“Così pochi si deliziano allo spettacolo sublime
che il cielo apparecchia invano
per un’umanità addormentata.”
Francois Xavier De Maistre, Spedizione notturna intorno alla mia camera.