Detection of helicoidal motion in the optical jet of PKS 0521–365

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
The jet activity of Active Galactic Nuclei (AGN), and its interaction with the interstellar medium (ISM), may play a pivotal role in the processes which regulate the growth and star formation of its host galaxy. Observational evidence which pinpoints the conditions of such interaction is paramount to unveil the physical processes involved. We report on the discovery of extended emission line regions exhibiting an S-shaped morphology along the optical jet of the radio-loud AGN PKS 0521–365 (z = 0.055), by using long-slit spectroscopic observations obtained with FORS2 on VLT. The velocity pattern derived from the [O II] λ3727 Å, Hβ λ4861 Å and [O III] λλ4959,5007 Å emission lines is well-fitted by a sinusoidal function of the form: 
v(r) = α(r^1/2 sin(βr^1/2 + γ)),
suggesting helicoidal motions along the jet up to distances of 20 kpc. We estimate a lower limit for the mass of the outflowing ionized gas along the jet of \( \sim 10^4 \, M_\odot \). Helical magnetic fields and jet precession have been proposed to explain helicoidal paths along the jet at pc scales; nevertheless, it is not clear yet whether these hypotheses may hold at kpc scales.

Key words: galaxies: active – ISM: jets and outflows – galaxies: individual (PKS 0521–365)

1 INTRODUCTION
The energy released by AGN is thought to significantly impact the evolution of its host galaxy (e.g. Fabian 2012; Kormendy & Ho 2013; King & Pounds 2015). Observational evidence of winds driving gas out of the nuclear regions (e.g. Holt 2008; Harrison et al. 2012; Combes et al. 2013; Morganti et al. 2013a,b; Dasyra et al. 2015; Morganti et al. 2015; Collet et al. 2016; Querejeta et al. 2016) suggests that outflows might be the main mechanism that could efficiently transfer energy from scales close to the black hole (pc) to host galaxy scales (kpc). These outflows – which arise as a by-product of accretion onto a black hole – are usually associated with either an accretion disk or radio jets (e.g. Croton et al. 2006; Krongold et al. 2007); nevertheless, the physical processes which regulate the interplay between the radio jet activity and the multi-phase gas remain unclear. On this regard, spatially resolving the interaction between an AGN and its host galaxy will provide key constraints on the physics and ubiquity of AGN feedback. For instance, long-slit spectroscopic studies have proved to be well suited to resolve jet-cloud interactions in nearby radio galaxies, suggesting strong interactions between the radio-emitting plasma and the ISM (e.g. Clark et al. 1997; Armus et al. 1998; Clark et al. 1998; Villar-Martín et al. 1999; Emonts et al. 2005; Inskip et al. 2008; Rosario et al. 2010b). On the other hand, Integral Field
Figure 1. Left panel: Optical HST image (WFPC2/F702W) of PKS0521−365 which features the host galaxy emission and the prominent jet. The contours represent the VLA radio map at 15 GHz (contour levels: -1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 512 mJy beam$^{-1}$; Falomo et al. 2009). Solid white rectangle shows the position of the slit (PA=−61.0°). Right panel: Residual image obtained after modeling and subtracting the host galaxy and nucleus contribution with Galfit. The diffuse emission along the major axis of the host galaxy might be closely related with the structure perpendicular to the radio jet detected with ALMA (Leon et al. 2016). The contour levels correspond to the VLA radio map at 15 GHz described above.

Spectroscopy (IFS) is particularly useful to disentangle the kinematical components and ionization state of complex extended emission line regions which are not only limited to the radio jet axis (e.g. Solórzano-Iñarrea & Tadhunter 2003; Inskip et al. 2008; Santoro et al. 2015).

PKS0521−365 is one of the most studied radio-loud AGN in the southern sky. Yet, there is no robust observational evidence on the effect of the AGN activity on its host galaxy (e.g. Hyvönen et al. 2007). Therefore it becomes one of the most accessible targets ($z = 0.05548$) for spatially resolving the trace that powerful jets leave on its host galaxy. Classified as a Flat Spectrum Radio Quasar (FSRQ) (Scarpa et al. 1999), it shows a large-scale optical/near-IR/sub-mm jet well aligned with the kpc radio jet (Scarpa et al. 1999; Falomo et al. 2009; Leon et al. 2016, see Fig. 1). Recently, a diffuse and extended structure perpendicular to the radio jet was detected in bands 3 and 6 with ALMA, which may be related with the relic of a previous jet or thermal (dust) emission associated with a central star-forming region (Leon et al. 2016). In this letter we report the discovery of extended emission line regions exhibiting an S-shaped morphology which suggests helicoidal motions along the jet of PKS0521−365 at kpc scales, providing new evidence on the way that AGN jets interact with the ISM. We report in Section 2 the details of the observations, followed by the results and analysis in Section 3. A discussion is given in Section 4. A cosmology with $H_0=70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m=0.30$, and $\Omega_{\Lambda}=0.70$ is assumed, corresponding to a luminosity distance for PKS0521−365 of 247.6 Mpc and a scale of 1.078 kpc arcsec$^{-1}$.

2 OBSERVATIONS

We secured long-slit spectra along the direction of the optical jet of PKS0521−365 (PA=−61.0°, see Fig. 1) with the Very Large Telescope (VLT), using the FOcal Reducer/ low dispersion Spectrograph 2 (FORS2 Appenzeller et al. 1998) and the GRIS 600B+22 (wavelength range 3300-6210 Å, dispersion 50 Å/mm). Three consecutive spectra of 850s integration time each were obtained during December 12, 2008 under good atmospheric conditions (seeing≈0.7; air mass≈1.1). The data reduction was performed using the standard procedures with IRAF. In the first stage, bias subtraction, flat fielding and removal of bad pixels were applied. Then, wavelength calibration, background subtraction were performed before combining the three spectra into a single spectrum. Flux calibration was performed after extracting 1D spectra along the spatial axis by using the standard star LT2415B. This result in a long-slit spectrum which encompass emission from the central engine and the optical jet with adequate spectral resolution (FWHM$_{sky-lines}$=4.5 Å) and high S/N (~100).

To pinpoint the spatial region covered by our long-slit spectroscopic data, we also use the HST image of PKS0521−365 using WFPC2 in the R (F702W) filter (Scarpa et al. 1999). The optical image was modeled using the galaxy fitting algorithm Galfit. We use the point spread function (PSF) model, obtained with the HST PSF modeling tool Tiny Tim, to represent the nuclear region of the galaxy. Similarly, we used a Sérsic profile convolved with the PSF to represent the host galaxy. According to our analysis, the host galaxy of PKS0521−365 is (as expected) a giant elliptical with a Sérsic index $n=3.96±0.41$, an effective radius $R_e=(4.74±0.55)$ kpc, an ellipticity $E=0.23±0.10$ and a magnitude $m=18.13±0.52$ ($M=-18.88±0.52$), well in accordance with previous analysis on PKS0521−365 (Urry et al. 2000) and typical values of blazars hosts (Oliugín-Iglesias et al. 2016). In the right panel of Fig. 1, we show the optical HST image when we subtract the modeled nucleus and host galaxy, revealing an optical jet which displays knotty morphologies and reassembles the structure of the radio jet.

3 RESULTS

Long-slit spectroscopy has revealed a large number of extended emission line regions aligned with the radio jet axis of radio-loud AGN. The spatial extent, ionization state and velocity fields of these regions have been examined in some detail (e.g. Best et al. 1997; Scarpa et al. 1999; Villar-Martín et al. 1999; Emonts et al. 2005; Rosario et al. 2010a,b;
Liuzzo et al. (2011). In this work, we report on the finding of extended emission line regions along the optical jet of PKS 0521−365. In the 2D spectrum (see Fig. 1, 2), the warped and knotty emission line [O II] λ3727 Å, Hβ λ4861 Å and [O III] λ4959, 5007 Å spread along the spatial axis towards the direction of the optical jet, which suggests ongoing jet-cloud interactions. In fact, this emission corresponds to the emitting knots traveling along the jet revealed by the HST imaging (see Fig. 1). We do not detect extended emission in the direction of the counter-jet in our long-slit spectroscopic nor optical imaging data (see Fig. 1, 3); which might be due to the fact that relativistic beaming enhances the approaching jet flux and dim the receding one (Leon et al. 2016).

The optical 1D spectra from the optical jet emission and the central engine were obtained by co-adding emission along the spatial axis in the 2D spectrum (see Fig. 3). In the first case, we integrate emission spreading up to ~10 arcsec from the nucleus and neglect that from the inner ~1.5 arcsec which is contaminated by broad line emission. In physical units, this corresponds to an area of ~8.5 kpc x 1 kpc, without correcting for the jet orientation. Similarly, to get the spectrum from the central engine we integrate emission from the inner kpc. As expected, the spectrum of the optical jet emission exhibits strong [O II] λ3727 Å and [O III] λ5007 Å narrow emission lines as well as stellar absorption features. On the other hand, the spectrum from the nucleus is dominated by the central engine by strong and broad Hβ λ4861 Å line emission along with narrow emission lines.

The spectral coverage of the spectra (3500−6000 Å) does not allow to detect the [OI] λ6300 Å, Hz λ6563 Å and [S II] λ6717, 6731 Å emission lines; which are essentials to probe the physical conditions (density, temperature) and disentangle the ionization mechanism of the emitting gas by using nebular emission line diagnostic diagrams (e.g. BPT diagrams). Thus, probing the ionization state of the gas is beyond the scope of this work. Nevertheless, we profit from the intermediate spectral resolution and high S/N of our spectra to examine the radial velocity patterns of the diffuse and warped emission lines spreading along the optical jet of PKS 0521−365 (see Fig. 2, 3).

### 3.1 Velocity profile

To explore the kinematics of the gas clouds along the optical jet we extract their spatial profile from the 2D spectrum. We first remove the “contamination” by adjacent continuum emission in the 2D spectrum (which spread over a few arcsec along the spatial axis) with the task continuum in IRAF. We integrate the emission (detected above 3-σ) in the 2D spectrum along the spatial axis in bins of 5 pixels – our spatial resolution is ~4.5 pixels, where 1 pixel = 0.126 arcsec. A single Gaussian function is fitted to each line in order to obtain the amplitude, σ and central wavelength of the line profile; from the latter parameter, we estimate the velocity offset with respect to the systemic velocity of the host galaxy.

Given that stellar features in the spectrum from the nucleus are shallow, we use narrow emission lines ([O II] λ3727 Å, [O III] λ4959, 5007 Å) associated with the central engine to derive the systemic velocity. We do not use any constraint on the separation or line ratio of the [O III] doublet in order to obtain independent measurements. It should be noted that the spectral resolution, given by the FWHM from the skylines (FWHM_{sky-line}=4.5 Å), suffices to resolve the emission spreading within a spectral range of ~15 Å (in the case of [O II] λ3727 Å and [O III] λ5007 Å).

The velocity profile along the optical jet derived from the four lines is shown in Fig. 4. Although the velocity swings are evident in the 2D spectrum, we perform a chi-square goodness of fit test to explore whether our data points can be described by a constant function, \( v(r) = v_c \), where \( v_c \) is the mean velocity in km s\(^{-1}\) along the spatial axis. We derive \( \chi^2 = 28 \) – with 44 degrees of freedom – which yield a
where \( v(r) \) is the velocity in \( \text{km s}^{-1} \), \( r \) is the distance in kpc and \( \alpha, \beta \) and \( \gamma \) are constants to be determined. We use a non-linear least-squares (Levenberg-Marquardt) algorithm to find the best-fitting values for these constants: \( \alpha = (64 \pm 4) \text{km s}^{-1} \text{kpc}^{-1/2} \), \( \beta = (-2.8 \pm 0.12) \text{kpc}^{-1/2} \) and \( \gamma = -11.8 \pm 0.3 \). This function describes a sinusoidal movement of ionized matter along the jet; where both, amplitude and period, increase with the distance. The farthest detected emission lies at 10 kpc – without correcting by the jet orientation – and the projected velocity reaches a maximum of 200 \( \text{km s}^{-1} \). In fact, under the conservative assumption of having a viewing angle of 30\(^\circ\) (Pian et al. 1996; Giroletti et al. 2004) the optical emission along the jet would extend up to 20 kpc.

In order to discern if the observed velocity shifts in the emission lines are consistent with the proposed model, we apply a Kolmogorov-Smirnov (K-S) test (Press et al. 1986). We simulated a sample of distance values by Monte Carlo simulations, then velocity shift values were obtained from the sinusoidal function, for each simulated value. By comparing the observations to the generated sample drawn from a distribution based on the sinusoidal model, we obtained a K-S statistic of 0.15 and a significance level of the K-S statistic of 0.61. Such high significance level points towards the null hypothesis being correct. From the K-S analysis, we conclude that both samples, observed and simulated, are drawn from the same parent distribution; which strengthens the argument of the sinusoidal motion along the jet.

### 3.2 Mass outflow along the jet

If the gas in a line-emitting region is primarily photoionized, the mass of the gas can be estimated from the \( \text{H}\beta \) luminosity as follows (Osterbrock 1989),

\[
M_{\text{gas}} = m_p \frac{L(\text{H}\beta)}{n_e \alpha_{\text{eff, H}\beta} \hbar \nu_{\text{H}\beta}}
\]

where \( n_e \) is the electron density in \( \text{cm}^{-3} \), \( m_p \) is the mass of a proton in kg, \( L(\text{H}\beta) \) is the \( \text{H}\beta \) luminosity in \( \text{erg s}^{-1} \), \( \alpha_{\text{eff, H}\beta} \) is the effective recombination coefficient for \( \text{H}\beta \) in \( \text{cm}^{-3} \text{s}^{-1} \) and \( \hbar \nu_{\text{H}\beta} \) is the energy of an \( \text{H}\beta \) photon in erg. We are assuming \( T = 10000 \text{K} \), since this is a typical temperature for a photoionized line emitting region (Osterbrock 1989).

We apply the STARLIGHT code (Cid-Fernandes et al. 2005) to the spectrum from the optical jet emission to subtract the host galaxy contamination and AGN non-thermal continuum. Before running STARLIGHT the spectrum was corrected for Galactic extinction assuming the \( E_{B-V} \) values computed by Schlegel et al. (1998). We estimate \( F_{\text{H}\beta} \sim 5 \times 10^{-16} \text{erg s}^{-1} \text{cm}^{-2} \); this value should be considered as a lower limit since the width of the slit itself (1 arcsec) does not allow to recover the entire extended emission along the jet. We consider typical densities of extended emission-line regions aligned with the radio axis which have been reported in the literature (e.g., Emonts et al. 2005; Nesvadba et al. 2006, 2008; Rosario et al. 2010b). In general, derived values for the density in extended emission-line regions – where the jet is strongly interacting with the host – range from 200 to 1000 \( \text{cm}^{-3} \), which yields a mass of \( 10^{5.1} \text{M}_\odot \) and \( 10^{4.4} \text{M}_\odot \) respectively. This result is in agreement with previously reported masses of jet-induced outflows of ionized gas, which
are of the order of $10^{4-5} M_\odot$ (Emonts et al. 2005; Rosario et al. 2010a,b). Naturally, these values are considered as lower limits for the total outflowing gas mass, as neutral and molecular gas might be present as well.

4 DISCUSSION

We found ordered emitting gas motions along the jet of the active galaxy PKS 0521–365 with a mass of at least $10^5 M_\odot$. Evidence of bright optical knots tightly aligned along the jet in radio galaxies has been already reported in the past; for instance, in 3C 266, 3C 324, 3C 368, 3C 371, PKS 2201+044 and PKS 2250–41 (Best et al. 1997; Scarpa et al. 1999; Villar-Martín et al. 1999; Liuuzzo et al. 2011). Such alignments suggest that strong interactions are taking place between the jet and the line-emitting gas which might derive into jet-triggered star formation (Tremblay et al. 2015; Donahue et al. 2015). In this work, we report the finding of narrow-line emitting gas oriented along the jet of PKS 0521–365 and provide insights about the kinematic of these regions. We found that the gas radial velocity patterns can be well described by a sinusoidal function, giving the first spectroscopic evidence of helicoidal motions along the jet on kpc scales.

Very Long Baseline Interferometry (VLBI) studies have revealed that helical structures are common in extragalactic jets in pc scales (e.g. Lister et al. 2003). They are usually associated with helical magnetic fields which are linked to the rotation of the central black hole and its accretion disk together with the jet outflow (Steffen et al. 1995; Keppens et al. 2008). On the other hand, helical structures may be a consequence of jet precession caused by a supermassive binary black hole system (SBBH) or the accretion disk; the gas accretion – possibly driven by minor mergers – is likely to occur at random angles (Roos et al. 1993; Oosterloo et al. 2004; Lu & Zhou 2005; Aalto et al. 2016). Hence, the S-shaped jet morphologies may reflect the fact that their black hole spin axis is still precessing and has not had sufficient time to align with the accretion disk. In particular, the presence of a SBBH or recent merging activity in PKS 0521–365 remains an open question. The later models have proved to be well suited to the observations in pc scale jets, nevertheless, what remains puzzling is at what extension these models can predict a helical path. Further theoretical and observational studies are needed to reconcile these approaches with the extent of the kpc-scale jet of PKS 0521–365 which shows signs of helical structures.

PKS 0521–365 is a multifaceted object which is undergoing a high-energy episode. It represents a unique opportunity to further inspect in detail the kinetic influence and ability of radio jets to drive gas outflows and interact with the ISM of its host galaxy; in particular, to understand how radio jets can transfer energy and redistribute mass up to galactic scales, and whether they can drive star formation in the timescales that they are acting upon the gas.

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