QSO HE 0435-5304 redshift solved

Małgorzata Bankowicz[1], Aleksander Herzig[1],
Agnieszka Pollo[1,2] and Katarzyna Małek[2]

1. Astronomical Observatory of the Jagiellonian University, ul. Orla 171, 30-244 Kraków, Poland
2. National Centre for Nuclear Research, ul. Pasteura 7, 02-093 Warsaw, Poland

We report a spectroscopic redshift measurement of quasar HE 0435-5304. Up to now, this particular quasar had two conflicting values of redshift used in the literature: 1.231 measured from an optical spectrum by Wisotzki et al. (2000), and ~ 0.43 obtained based on ultraviolet spectra by Stocke et al. (2013). The $z = 1.231$ value is more widely used and listed as the "preferred redshift" in the NASA/IPAC Extragalactic Database and SIMBAD databases. However, combined with photometric multiwavelength measurements, this redshift value makes the HE 0435-5304 host a very extreme and even peculiar galaxy in terms of star formation, as found by Małek et al. (2017), while at $z \sim 0.43$ HE 0435-5304 remains a fairly typical example of a Luminous Infrared Galaxy. To clarify this issue, we analysed an optical spectrum of HE 0435-5304 obtained by the Robert Stobie Spectrograph at the South African Large Telescope (SALT) as a part of our project to study properties and environments of infrared sources around the South Ecliptic Pole. Based on five clearly identified emission lines we estimated the redshift of this quasar to be $z = 0.45$, in agreement with the value reported by Stocke et al. (2013), and definitely ruling out the "preferred redshift" value by Wisotzki et al. (2000).

1 Introduction

HE 0435-5304 is an optically bright quasar, located in the southern sky, with the V magnitude $m_V = 16.40$ (Véron-Cetty & Véron, 2010; Souchay et al., 2015). It was also recently observed by the Gaia satellite with the G magnitude $m_{\mathrm{G}} = 17.45$ (Gaia Collaboration et al., 2018). It is also a bright ultraviolet (Seibert et al., 2012; Monroe et al., 2016) and infrared source (e.g., Cutri et al., 2003). In particular, it has been detected at 90μm by the AKARI space telescope, as a part of the Akari Deep Field - South survey (ADF–S; Shirahata et al., 2009).

The redshift of HE 0435-5304 has been first measured as $z = 1.231$ by Wisotzki et al. (2000), who published a catalogue of 415 bright quasars and Seyfert-1 galaxies from the Hamburg/ESO survey. This value is still given as a "preferred redshift" by the NASA/IPAC Extragalactic Database (NED[1]) and by the SIMBAD Astronomical Database[2].

HE 0435-5304 was and is being extensively used for studies of circumgalactic medium, namely of an extended halo of a nearby spiral galaxy ESO 157-49. For this purpose, Stocke et al. (2013) measured its redshift based on two lines found in the ultraviolet (UV) spectrum obtained by the Hubble Space Telescope Cosmic Origins Spectrograph instrument (HST COS) and found a value $z = 0.425$. This value was consistently used for studies of circumgalactic medium by the same group (Keeney

[1] https://ned.ipac.caltech.edu
[2] http://simbad.u-strasbg.fr/simbad/

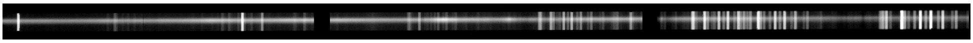

Fig. 1: Spectrum of HE 0435-5304 obtained through the MOS exposure, after reduction. Two black gaps are clearly visible.

et al., 2013; Danforth et al., 2016; Keeney et al., 2017, 2018). On the other hand, Neeleman et al. (2016) included the same HST COS UV spectrum of HE 0435-5304 in his sample of quasar UV spectra used to search for the damped Lyα absorbers and used its "preferred" $z = 1.231$ originally measured by Wisotzki et al. (2000). Needless to say, the interpretation of the absorption lines in the quasar spectrum depends heavily on interpretation of the features in the spectrum of the quasar itself, and this relies on the value of its redshift.

HE 0435-5304 is also a bright far-IR object. As such, it was included in the studies of star forming galaxies, Luminous and Ultraluminous IR Galaxies (LIRGs and ULIRGs) conducted in the ADF–S by Małek et al. (2014, 2017). Fitting its UV-to-IR spectral energy distribution (SED), and assuming its "preferred" redshift $z = 1.231$, Małek et al. (2017) found HE 0435-5304 to be an extreme Hyperluminous IR Galaxy (HLIRG), with dust luminosity $\log L_{\rm dust} = 13.12 \pm 0.09 L_{\odot}$, and star formation and other dust properties strongly deviating from the usual trends for IR-bright galaxies. Thus, at $z = 1.231$ HE 0435-5304 would be a very peculiar object, joining quasar activity with an extreme (even for quasar host galaxies) star formation. On the other hand, the best fitted photometric redshift of this object found with the aid of the SED fitter CIGALE (Noll et al., 2009) was found to be $z_{\rm phot} = 0.3$. With this value and with the value of redshift $z = 0.425$ given by Stocke et al. (2013), the best fitted SED of HE 0435-5304 indicates that it is a rather average LIRG with dust luminosity $\log L_{\rm dust} = 11.12 \pm 0.29 L_{\odot}$, and with star formation rate and other physical properties following relations very similar to those of other galaxies of this class at similar redshift.

Given that HE 0435-5304 is a potentially an interesting object itself, allowing to study relations of quasar and star forming activity in the same galaxy, and, in the same time, its spectrum is used for studies of intergalactic absorption lines, it is worth to solve the discrepancy in its redshift measurement. In this proceeding we present preliminary measurement of redshift of this quasar, based on the optical spectrum obtained with the aid of the SALT telescope in the framework of a broader project of studies of local environments of star forming galaxies in the ADF–S.

2 Data and methodology

We were granted time on the Multi Object Spectroscope (MOS) mounted on the SALT telescope in the SAAO (South African Astronomical Observatory), as a pilot project for spectroscopic studies of properties and environments of galaxies detected in the far-IR in the ADF–S. One of our first targets was the quasar HE 0435-5304. Preparation of the MOS mask required one second long pre-imaging exposure of the selected field in order to obtain precise astrometric measurements of targets. This step was performed by the SALT team using SALTicam, which is a primary camera for the SALT telescope imaging. The image was acquired with the grey filter. Exposure time of one second was sufficient to provide the optimal depth

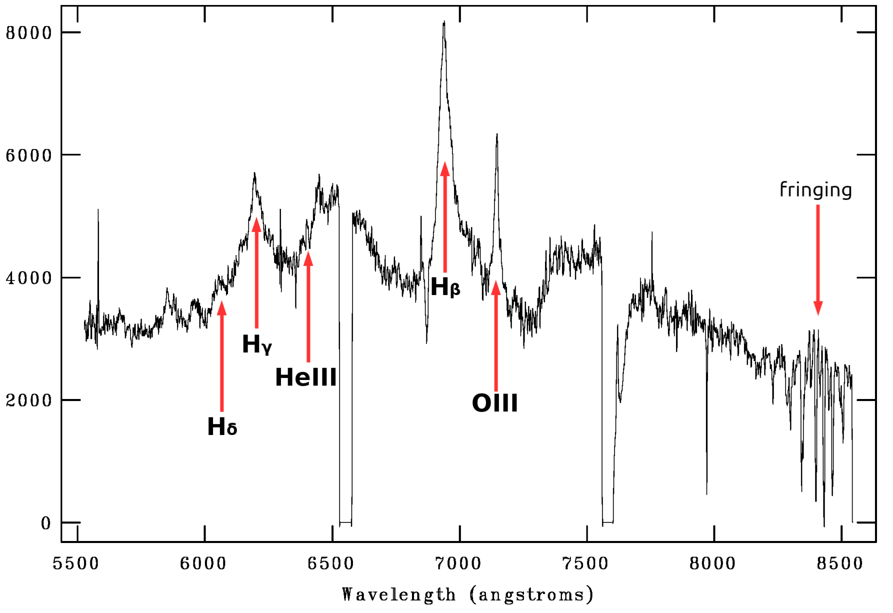

Fig. 2: Observed spectrum of the quasar HE 0435-5304. Identified lines are indicated by arrows.

for our intended targets. Subsequently, a spectroscopic mask of slits for the MOS observations was prepared.

MOS observations were made using Robert Stobie Spectrograph (RSS) with the prepared mask. One pointing allowed for measurements of 20 objects, among them 4 stars used for positioning of the mask in the acquisition field and 16 galaxies, including a quasar HE 0435-5304. The camera used consists of three separate CCD chips which results in visible gaps in the spectra (see Fig. 1). In order to cover these gaps, two different sets of spectra were acquired with a slight offset in target coordinates. Co-adding these spectra secured a coverage of these gaps.

MOS observations were performed with S/N ratio no less then 9, using diffraction grating of 900 $\mathrm{lines mm}^{-1}$ for wider spectra which covered range from 3602.8 Å to 6729.8 Å and slits 1.5 arcsec wide. Dispersion for these observations was 0.50 Å per pixel, spatial plate scale of 0.127 arcsec per pixel, and error estimate for the wavelengths is 30 Å. Resolution of these acquisitions is different for each of the three chips: blue chip centre for 4108.8 Å has a resolution of 733, middle chip centre with 5184.2 Å has a resolution of 925 and red chip centre 6243.0 Å has a resolution of 1113. Two data sets were acquired with slight offset for the gaps to cover different parts of the spectrum making it possible to create gapless spectra for every object. Every exposure needed 1.2 ks in order to acquire spectra of targets down to B filter magnitude of 23 which amassed to 4.8 ks of overall exposure time on four exposures.

MOS data from the SALT observation has been pre-reduced. Images were reduced for BIAS, DARK and flatfield images. As the first step, the DCR code (Pych, 2004) was used to remove cosmic rays, dead or hot pixels and other artifacts. Next steps were made with IRAF software (Tody, 1986, 1993). The IRAF procedures: *apall*, *identify*, *reidentify* and *splot* we used for viewing and measuring one dimen-

	λ_{lab}[Å]	λ_{obs}[Å]	z	$\sigma(z)$
H_δ	4102.890	6060.060	0.477	0.001
H_γ	4341.680	6189.855	0.426	0.011
HeIII	4364.436	6447.142	0.477	0.009
H_β	4862.680	6939.071	0.427	0.007
OIII	4932.603	7145.276	0.449	0.003
			0.449	0.003

Tab. 1: Lines identified in the spectrum of a quasar HE 0435-5304 with their rest-frame wavelengths λ_{lab} given in column 2, and observed, i.e. measured wavelengths λ_{obs} given in column 3. Redshift values measured for each line separately, together with corresponding errors, are listed in columns 4 and 5.

sional spectra. ARC lamps we used for wavelength calibration of spectral lines. The lamps were Copper-Argon (CuAr) and Thorium-Argon (ThAr) with known emission lines. Firstly, a procedure *apall* that have split our two dimensional images to separate spectra was used. After splitting these images, visible lines in images of calibration lamps were identified by the *identify* procedure. Subsequently, *reidentify* procedure was utilized to find these lines in our observations, thus calibrating images for the proper wavelength. Finally, using *splot* procedure, lines in the spectra themselves were identified. Gaussian and Lorentzian functions were fitted in order to create statistical sample of ten measurements of peak wavelength position for each identified line.

Based on these fitted profiles of the lines, redshift values were measured for each line separately, with error values computed based on from a standard deviation of each emission line measurement, a systematic error for RSS is $\Delta\lambda_{\text{o,s}} = 30$Å and a resolution R which is different for each of the three chips, and assumes a value 733, 925 and 1113 for the "red", middle and "blue" chip, respectively.

A final redshift value was calculated as a weighted mean of measurements for each line along with its error.

3 Results and summary

In the spectrum of HE 0435-5304 we identified five high-confidence broad emission lines: H_δ, H_γ, HeIII, H_β and OIII, as shown in Fig. 2. In Tab. 1 rest-frame and observed values of identified lines wavelengths are summarized, along with the corresponding redshift values and their errors.

A final redshift value was calculated as a weighted mean of redshift values measured for each identified line, with an error calculated as a weighted mean error. The resultant measured spectroscopic redshift of a quasar HE 0435-5304 is then 0.449 ± 0.003. This value is in a good agreement with redshift measured by Stocke et al. (2013) based on the UV spectra. Given that this measurement is based on as many as five high-confidence broad emission lines, it can be safely said that it disproves the "preferred" value of $z = 1.231$ by Wisotzki et al. (2000), which should be replaced in the databased by the new value $z = 0.449$. A more detailed study of properties of HE 0435-5304 as a LIRG, based on its combined spectroscopic and photometric data, will be presented by Bankowicz et al. (2020, in prep.).

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