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WHAT IS THE REDSHIFT OF THE GAMMA-RAY BL LAC SOURCE S4 0954+65?

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ABSTRACT

High signal-to-noise ratio spectroscopic observations of the BL Lac object S4 0954+65 at the alleged redshift $z = 0.367$ are presented. This source was detected at gamma frequencies by the MAGIC (TeV) and *FERMI* (GeV) telescopes during a remarkable outburst that occurred in 2015 February, making the determination of its distance particularly relevant for our understanding of the properties of the extragalactic background light. Contrary to previous reports on the redshift, we found that the optical spectrum is featureless at an equivalent width limit of $\sim$0.1 Å. A critical analysis of the existing observations indicates that the redshift is still unknown. Based on the new data we estimate a lower limit to the redshift at $z \geqslant 0.45$.

Key words: BL Lacertae objects: individual (S4 0954+65) – gamma rays: general

1. INTRODUCTION

BL Lac objects are extragalactic radio sources hosted in massive elliptical galaxies and are characterized by strong non-thermal synchrotron emission dominated by a relativistic jet closely aligned with the line of sight. From the spectroscopic point of view they exhibit a quasi-featureless optical spectrum that makes the detection of any emission/absorption line extremely difficult. For this reason, the redshift z of many BL Lacs is still unknown or highly uncertain. In particular, the quasi-featureless optical spectrum of BL Lacs is one of the main characteristic for this class of objects. This peculiarity made them rather elusive. The difficulty in detecting features has the direct consequence of not being able to measure their distance. Specifically, for low redshift targets the optical spectra with adequate signal-to-noise ratio (S/N) allow one to detect the absorptions lines from their host galaxies (typically a massive elliptical galaxy) while for higher redshift objects and very luminous (beamed) nuclei the situation is more challenging. In fact, only the availability of very high S/N spectra and relatively high spectral resolution could reveal faint features (see e.g., Sbarufatti et al. 2006; Landoni et al. 2013, 2014). In the most extreme cases where the nucleus-to-host ratio is severe (see Landoni et al. 2014), only intervening absorption features can be detected in the optical spectra and thus only sound lower limits to the redshift can be assessed. Nevertheless, the knowledge of the redshift is crucial not only to assess their cosmological role and evolution, which appears to be controversial due to redshift incompleteness (e.g., Ajello et al. 2014), but also to properly model their emission mechanism and energetics (see e.g., Falomo et al. 2014 and references therein). Moreover, BL Lacs (and blazars) are the dominant population of extragalactic sources detected at the highest energies in the γ-ray sky (e.g., Massaro et al. 2015 and Fermi LAT Collaboration 3FGL catalog). In many cases they are also detected at Very High Energy (VHE) with Cherenkov telescopes (e.g., MAGIC, Veritas and HESS, see the Chicago TevCat catalog[5] from Horan & Wakely 2008). It is consequently of the outmost relevance to know the distance of these sources to understand how extremely high energy photons propagate through space and interact with the extragalactic background light (Franceschini et al. 2008; Domínguez et al. 2011).

In this paper, we focus on the prototypical BL Lac object S4 0954+65 at the alleged redshift $z = 0.367$ that recently experienced a dramatic flare in the optical and near-IR band, and was detected for the first time at VHE band by the MAGIC telescope (Mirzoyan 2015). We present new optical spectroscopy obtained with the 10.4 m Gran Telescopio CANARIAS (GTC) aiming to firmly determine the redshift of the source.

2. S4 0954+65

This source was classified as a BL Lac object by Walsh et al. (1984) and exhibits all the properties of its class. In fact, in the optical band it is strongly variable with R apparent magnitudes usually ranging between 15 and 17 (e.g., Raiteri et al. 1999). During a flare which occurred in 2011, it brightened by 0.7 mag in 7 hr (Morozova et al. 2014). Linear polarization is also strongly variable and can be as high as 20%, with large changes of polarization angle (Morozova et al. 2014). The radio morphology is rather complex with jet-like structures appearing from pc to kpc scales. Superluminal moving components have been reported with apparent speeds up to $\sim 19c$ (Gabuzda & Cawthorne 2000; Kudryavtseva et al. 2010; Morozova et al. 2014). The object was studied also in the X-ray band (Perlman et al. 2006; Resconi et al. 2009) and it was one of the first detected extragalactic γ-ray sources (Thompson et al. 1995; The Fermi-LAT Collaboration 2015).

The first attempt to determine the redshift of this source was done by Lawrence et al. (1986) (L86) who proposed $z = 0.367$. Further optical spectroscopy was then obtained by Stickel et al. (1993) (S93) confirming this redshift. However, the two determinations of the redshift are mainly based on different spectral features casting some doubts on the soundness of the proposed redshift. Moreover, we note that, in spite of the low z, both ground based imaging (S93) and *Hubble Space Telescope* (*HST*) observations (Scarpa et al. 2000; Urry et al. 2000) failed to detect the underlying diffuse emission from the host galaxy, suggesting higher redshift for this source.

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[5] http://tevcat.uchicago.edu

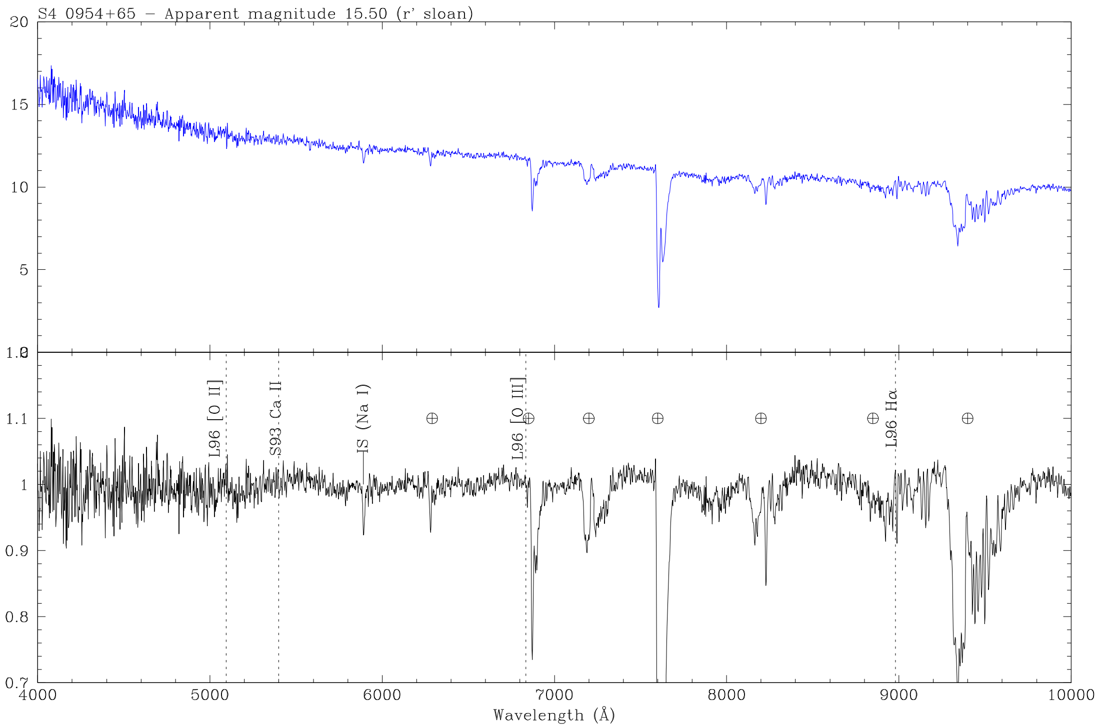

Figure 1. S4 0954+65 optical spectrum obtained with OSIRIS at GTC. Upper panel: flux calibrated spectrum of the source; Bottom panel: normalized spectrum. Interstellar absorption features are marked by ISM while telluric bands are marked by ⊕. The position of features claimed by Stickel et al. (1993) (S93) and Lawrence et al. (1996) (L96) are reported as vertical dotted lines (see text).

In 2015 February the target exhibited dramatic optical activity reaching $R \sim 13$ (Bachev 2015; Spiridonova et al. 2015 and references therein). This motivated a TeV observation with the Cherenkov telescope MAGIC, which detected the source with 5σ significance (Mirzoyan 2015). A simultaneous high, hard state was reported by FERMI Team (Ojha et al. 2015).

3. OBSERVATIONS AND DATA REDUCTION

Medium resolution ($R = 1000$) optical spectra were gathered at the GRANTECAN 10.4 m telescope located at the Roque de Los Muchachos observatory, La Palma, Spain. Data were obtained on the night of 2015 February 28. The telescope was equipped with the Optical System for Imaging and low-intermediate-resolution Integrated Spectroscopy (OSIRIS, Cepa et al. 2003). We observed the object with two grisms (R1000B and R1000R) in order to ensure a large spectral coverage (from ~0.42 to 1 μm) adopting a slit of $1''$. For each grism, we secured three individual exposures of 150 s each, in order to optimize cosmic-ray rejection and cosmetic cleaning. The seeing during the observations was $\sim 1''$ and the sky condition was clear. The accuracy of the wavelength solution (assessed through calibration lamps, sky emission lines and standard star spectra) is ~0.1 Å. At the time of observations the R (AB) magnitude of the source was 15.5 ± 0.2, as derived from a short exposure acquisition image.[6] This magnitude is much fainter (~2.5 mag) than the maximum values detected during the flare episode described above. Data reduction was carried out using IRAF[7] adopting standard procedures for long slit spectroscopy. The S/N of various bands of the spectrum ranges between ~50 at the bluest wavelength (4000–6000 Å), ~120 in the central region (6000–7500 Å) and ~90 in the reddest range. The optical spectrum is shown in Figure 1.

4. RESULTS

The spectrum of S4 0954+65 does not exhibit any intrinsic feature and the continuum is well described by a power law of the form $\lambda^{-\alpha}$ with spectral index $\alpha \sim 0.9$. This result is comparable with that proposed by Lawrence et al. (1996) and consistent with the mean value of the optical-near-IR spectral index for BL Lac objects (see e.g., Pian et al. 1994; Landoni et al. 2013). In addition to the prominent telluric absorption bands, we detect the interstellar absorption of ISM Na I with equivalent width (EW) ~ 0.80 Å. We then calculated the minimum equivalent width $\mathrm{EW_{min}}$ detectable on the spectrum in various bands, adopting the procedure described in Sbarufatti et al. (2006). In particular, we evaluated the EW on bins of the size of the resolution element in various regions of the spectrum excluding the telluric structures. We assume as $\mathrm{EW_{min}}$ the 2σ deviation from the mean of the average of the distribution of the EWs obtained in each bin. We found that the $\mathrm{EW_{min}}$ is ~0.15 Å in the region 4000–6000 Å, ~0.1 Å between 6000–7500 Å and ~0.2 Å in the reddest part.

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[6] A finding chart with a reasonable field of view is available at https://ned.ipac.caltech.edu/dss/HB89_0954+658.gif and can be useful for those who want to reproduce the observation.

[7] IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

The result from our spectrum contrasts with previous claims of detection of intrinsic emission and absorption features. Specifically, Lawrence et al. (1996) (L96), on the basis of the spectrum obtained in 1986 ($R \sim 400$), reported the detection of three weak narrow emission lines identified as [O II] ($\lambda_{\rm rest}$ 3727, EW$_{\rm rest}$ 0.5 Å) and [O III] ($\lambda_{\rm rest}$ 4959, EW$_{\rm rest}$ 0.3 Å; $\lambda_{\rm rest}$ 5007, EW$_{\rm rest}$ 0.7 Å) at redshift $z = 0.3668$. In addition, a broad emission line detected at the edge of their observed spectrum (EW 2.6 Å) was ascribed to Hα emission at about 8990 Å in the observer frame. A low resolution optical spectrum was obtained by S93 finding the emission line ascribed to [O II] λ3727 (EW 0.3 Å) but not confirming the [O III] emission line reported by L96. Note that EW of the [O III] line detected by L96 was greater than that of [O II]. On the other hand, S93 found also an absorption doublet at $\sim$5400 Å ascribed to Ca II$\lambda\lambda$ 3933–3968 from the host galaxy (not detected by L96 although the source was at a similar flux level).

In our new spectrum we cannot confirm any of the previous aforementioned absorption or emission lines. In particular, the [O II] λ3727 that would be observed at 5094 Å at $z = 0.367$ is not detected at the limit of EW$_{\rm min} \geqslant 0.15$ Å (see Figure 1). The [O III] $\lambda\lambda$ 4959,5007 narrow features that would appear at 6804 Å, very close to the prominent O_2 telluric absorption band, are again not detected at EW$_{\rm min} \geqslant 0.1$ Å. Moreover, we do not detect neither the absorption features of Ca II claimed by S93 (down to EW$_{\rm min} \geqslant 0.15$ Å), or the broad emission at $\sim$8990 Å proposed by L96 (heavily contaminated by the strong H_2O telluric band). Note also that this feature at the proposed redshift $z = 0.3668$ corresponds to a rest frame emission at 6580 (see Table 35 in L96), inconsistent with Hα (λ 6563).

It is worth noting that the continuum level during our observation was a factor of $\sim$2–3 higher than that reported in S93 and L96 (see e.g., magnitude reported in Table 1 in S93). Therefore, if the claimed detected features were unchanged in intensity, their EWs should be lowered by the same factor. Considering the dilution due to the enhanced continuum, we should have detected the [O III] λ 5007 at EW $\sim$ 0.3 Å, 3 times higher than our EW$_{\rm min}$. This consideration also applies for Hα emission while it is not possible to give an estimation for the Ca II lines (S93) since EWs are not reported.

Based on our high SNR spectrum, we can estimate a lower limit to the redshift following the recipe described in Sbarufatti et al. (2006) and Landoni et al. (2014). Briefly, assuming that the BL Lac is hosted by an average elliptical galaxy with $M_R = -22.9$ it is possible to infer a lower limit of the redshift from the EW$_{\rm min}$ and the apparent magnitude of the source (see Equation (1) in Landoni et al. 2014). This procedure applied to the spectrum of S4 0954+658 yields $z \geqslant 0.45$. This lower limit is consistent with the non detection of the host galaxy from direct imaging (see S93 and Scarpa et al. 2000).

5. CONCLUSIONS

We presented a high quality optical spectrum of the bright BL Lac object S4 0954+65 that disputes the previously claimed redshift $z = 0.367$ adopted in the last $\sim$30 years. Based on the new spectroscopic observation we estimate a lower limit to the redshift of $z > 0.45$. Nowadays, the population of BL Lacs detected at gamma frequencies at GeV and, in particular, at TeV energies is fast growing. Thanks to their emission at VHE, they can be used as a natural probe for the characterization of the properties of the extragalactic background light (see e.g., Franceschini et al. 2008; Domínguez et al. 2011). The knowledge of the redshift of the sources (or a lower limit) is therefore mandatory to these studies. In this context, the case of S4 0954+658 is rather prototypical. On the basis of a number of observable quantities such as the apparent magnitude, point like images, featureless spectrum and their γ-ray emission, S4 0954+65 appears similar to few other bright BL Lacs objects such as PG 1553+113 ($R \sim 14$) and H 1722+119 ($R \sim 15$, Landoni et al. 2014). The determination of the redshifts for these extreme sources would require a major improvement of the spectroscopic capabilities as those expected to be available with the future European Extremely Large Telescope (see e.g., Landoni et al. 2013, 2014). Alternatively, using a complementary approach to this kind of sources, one can detect Lyα forest absorptions from UV spectra to derive a redshift limit (c.f *HST*/COS observation by Danforth et al. 2010). Second, S4 0954+65 has been detected at a threshold energy of hundred of GeVs (see Mirzoyan 2015) where the opacity due to γ–γ interaction is strongly dependent on the redshift (about a factor of $\sim$2 between 0.35 and 0.45, see Franceschini et al. 2008; Domínguez et al. 2011). In this framework, the newly available estimation of the lower limit of the source will play an important role, especially in the reconstruction of the VHE tail of the emission spectrum of the source, as traditionally assessed for TeV sources absorbed by EBL interaction (Prandini et al. 2010). In this case, the knowledge of the z is decisive to reconstruct the intrinsic, unabsorbed spectrum and then apply the model of emission mechanisms (Ghisellini et al. 2005) to recover the physical state of the source (magnetic field, black hole mass, etc.).

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