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Letter to the Editor

Detection of the host galaxy of S5 0716+714

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ABSTRACT

We have acquired a deep *i*-band image of the BL Lacertae object S5 0716+714 while the target was in an low optical state. Due to the faintness of the nucleus, we were able to detect the underlying host galaxy. The host galaxy is measured to have an *I*-band magnitude of 17.5 ± 0.5 and an effective radius of (2.7 ± 0.8) arcsec. Using the host galaxy as a "standard candle", we derive $z = 0.31 \pm 0.08$ (1σ error) for the host galaxy of S5 0716+714. This redshift is consistent with the redshift $z = 0.26$ determined by spectroscopy for 3 galaxies close to S5 0716+714. The effective radius at $z = 0.31$ would be 12 ± 4 kpc, which is consistent with values obtained for BL Lac host galaxies. An optical spectrum acquired during the same epoch shows no identifiable spectral lines.

Key words. galaxies: active – galaxies: distances and redshifts – BL Lacertae objects: individual: S5 0716+714

1. Introduction

BL Lacertae objects (BL Lacs) are active galactic nuclei (AGN) characterized by a featureless nonthermal continuum, high optical and radio polarization, and variability across the entire electromagnetic spectrum. These properties arise from a relativistic jet pointed almost towards the observer (Blandford & Königl 1979). The strong continuum emission from the jet in the optical sometimes presents a problem when attempting to properly characterize the underlying host galaxy or measure its redshift, especially since by definition the emission lines are very weak in BL Lacs. Hence, it is unsurprising that even after very deep searches (e.g. Sbarufatti et al. 2006) many BL Lacs remain without a spectroscopically determined redshift.

The redshift is a fundamental property of any extragalactic object, without which e.g. the luminosity or intrinsic variability properties of the target cannot be determined. Furthermore, many BL Lacs have been recently detected at TeV gamma-rays using ground-based Cherenkov telescopes MAGIC, HESS, and VERITAS (e.g. Hinton 2007). Since VHE gamma-rays can be absorbed by the interaction with low energy photons of the EBL via pair production, this opens the possibility of measuring the amount of extragalactic background light (EBL, Nikishov 1962; Stecker et al. 1992) in the optical through to the far infrared, which provides important information about the galaxy and star formation history. The absorption depends strongly on the distance of the source and the energy of the gamma-rays. If the redshift of the source is known, the VHE gamma-ray spectrum can be used to derive limits on the EBL (e.g. Aharonian et al. 2006; Mazin & Raue 2007). On the other hand, if the redshift is unknown, the VHE gamma-ray spectra can be used to set an upper limit to the redshift of the source (e.g. Mazin & Goebel 2007).

After its discovery as a bright ($S_{5\ \mathrm{Ghz}} > 1$ Jy) flat-spectrum ($\alpha \leq -0.5$, $S_\nu \propto \nu^\alpha$) radio source, the BL Lac object S5 0716+714 has been studied intensively at all frequency bands. The object is highly variable with rapid variations observed from radio to X-ray bands (Wagner et al. 1996; Ostorero et al. 2006). The nucleus of S5 0716+714 is typically bright in the optical (see e.g. Nesci et al. 2005), thus previous attempts to either characterize its host galaxy (Stickel et al. 1993; Urry et al. 2000; Pursimo et al. 2002) or to determine its redshift spectroscopically (Stickel et al. 1993; Marchã et al. 1996) have not been successful. Thus, in spite of numerous variability studies of S5 0716+714, it has never been possible to determine reliably e.g. the linear dimensions and luminosities of the varying components.

S5 0716+714 has also been detected in TeV gamma-rays (Teshima et al. 2008). Given that previous estimates (e.g. Wagner et al. 1996) place S5 0716+714 at $z > 0.3$, this would make the target one of the most distant TeV sources detected so far. Given the obvious importance of S5 0716+714 to EBL studies, it is be important to secure an accurate spectroscopic redshift for S5 0716+714 or at least constrain the redshift by some other means.

S5 0716+714 is regularly monitored at Tuorla Observatory as part of the blazar monitoring program[1]. On December 17, 2007 we observed S5 0716+714 to go into a fairly deep optical minimum ($R \sim 14.8$) and initiated prompt *i*-band imaging at the Nordic Optical Telescope (NOT) to detect its host galaxy. The imaging was performed five days after the minimum and the results are reported in this Letter.

Throughout this Letter, we use the cosmology $H_0 = 70\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\mathrm{M} = 0.3$ and $\Omega_\Lambda = 0.7$.

2. Observations and data analysis

S5 0716+714 was observed at the Nordic Optical Telescope (NOT), La Palma on Dec. 22, 2007. We used the ALFOSC instrument in imaging mode with a 2k E2V CCD chip of a gain

[1] http://users.utu.fi/~kani/1m/index.html

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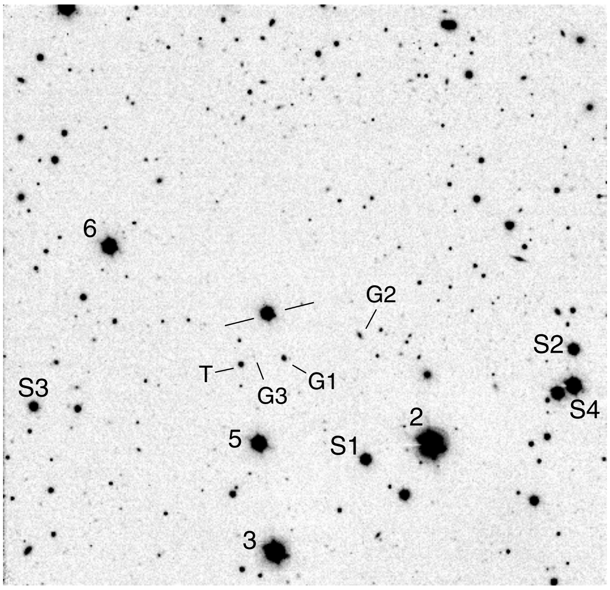

Fig. 1. The summed i-band image of S5 0716+714 obtained at the NOT in Dec. 22, 2007. The field size is 3.85×3.7 arcmin, north is up and east is to the left. Object T is a transient or a very red object not visible in previous images of S5 0716+714, most of which were obtained in the R-band. The other labeled objects are discussed in the text.

0.726 e$^-$ ADU^{-1} and readout noise 3.2 electrons. Twenty-eight exposures of 45 s were acquired using an i-band interference filter of almost uniform transmission between 725 and 875 nm, which provided a total exposure time of 1260 s. The i-band filter was chosen because it detects light above the 4000 Å break of the host galaxy even at $z = 0.5$, which maximizes the amount of light from the host galaxy.

The individual images were bias-subtracted and flat-fielded with twilight flats in the usual way using IRAF[2]. A fringe pattern with an amplitude of ~2.5% of the sky background was visible in the reduced images. A fringe correction image was produced by median combining all 28 images and applying simultaneously a sigma clipping cut to the pixel intensity values. Since the position of S5 0716+714 on the CCD was altered between the exposures, this procedure produced a clean correction image consisting purely of the fringe pattern. After correction for the fringe pattern, the individual frames were registered and summed. The summed image shown in Fig. 1 has a $FWHM$ of 0.80 arcsec and the sky background is flat within 0.4% over the entire field of view.

The field was calibrated using stars 3, 5, and 6 for which Ghisellini et al. (1997) published Cousins I-band magnitudes. Unfortunately, all three stars were saturated in their cores (r < 0.″4–0.″8), and could not be used directly for calibration purposes. Instead, we used a 45 s i-band exposure of the field acquired immediately before the S5 0716+714 sequence. The $FWHM$ in this image is significantly worse than in the S5 0716+714 sequence and stars 3, 5, and 6 are not saturated. Using these stars we first determined the zero point of the 45 s exposure. All three stars gave consistent results, the maximum difference between the zero points was 0.047 mag, consistent with the errors of the I_C magnitudes 0.04–0.05 mag in Ghisellini et al. (1997). Using this zero point, we determined the I_C magnitudes of stars S1, S2, and S3 and from these three stars the zero point of the combined long exposure. The uncertainly in the zero point was dominated by the uncertainty in the I_C magnitudes of stars 3, 5, and 6 and by the color effects between our i-band filter and the I_C filter. We estimate the former contribution to the uncertainty to be 0.03 mag.

To estimate the magnitude of the color effects, we used the established relation between I_C and and SDSS i given by Lupton (2005) in the SDSS web pages[3]: $I = i - 0.3780(i - z) - 0.3974$. The SDSS i has approximately the same width as our i-band filter, but the central wavelength is ~50 nm lower. For stars 3, 5, and 6, the $i - z$ color is ~–0.01–0.06. Assuming stars S1-S3 have similar colors and since an elliptical galaxy at $z = 0.3$–0.5 has a color $i - z \sim 0.4$–0.5, the color effects between the calibration stars and the host galaxy of S5 0716+714 may cause an error of up to 0.2 mag in SDSS i. Since our filter is close to SDSS i, we expect the color effects to be similar in value. Since the color errors dominate the total error of the zero point, we assign a formal error of 0.2 mag to the magnitude zero point.

The host galaxy was analyzed by fitting a two-dimensional surface brightness model to the light distribution of S5 0716+714. Details of this process can be found in Nilsson et al. (1999). In short, the model consists of two components, an unresolved core representing the BL Lac nucleus and a de Vaucouleurs profile representing the host galaxy. Previous imaging (e.g. Urry et al. 2000) has shown that the de Vaucouleurs profile describes well the surface brightness profiles of BL Lac host galaxies, although deviations from this law have also been observed (e.g. Nilsson et al. 2003). For our purposes, it is sufficient to know that BL Lac host galaxies are bulge-dominated systems and no BL Lacertae object has ever been reliably associated with a disk type host.

The model is described by 5 parameters: position (x, y), core magnitude m_C, host galaxy magnitude m_H, and host galaxy effective radius $r_{\rm eff}$. The model parameters are adjusted using an iterative Levenberg-Marquardt loop, until the minimum value of the χ^2 statistic between the model and the data is found. Only pixels within 9.″5 from the center of S5 0716+714 were included in the fit and pixels influenced by an $I = 20.8$ mag nearby companion 4.″2 west of S5 0716+714 were excluded.

The model is convolved by the observed PSF, determined from stars in the vicinity of S5 0716+714. Since stars 5 and 6 were saturated in their cores (r < 0.4 arcsec; the peak counts of S5 0716+714 remained under 58 000 ADUs in all images), we constructed the PSF from stars 5 and S1 by joining smoothly the outer parts of star 5 with the inner part of S1 (hereafter we refer to this PSF as PSF1). A second PSF was constructed in a similar way from stars 6 and S2 (PSF2) to study the effect of PSF variability over the field of view.

Since the host galaxy is faint compared to the nucleus, the results are highly dependent on the accuracy of the PSF and its stability over the field of view. We analyzed the PSF stability by extracting the surface brightness profiles of stars 2, 3, 5, 6, S1, and S2 and scaling them to the same magnitude. In the lower panel of Fig. 2, we show the surface brightness profiles of these stars relative to star 5, which is equal to PSF1 at r > 0.″4. We note that in this representation star 5 appears as a horizontal line. The surface brightness profiles of the stars agree to within 0.2 mag all the way to the outer fitting radius of 9.″5. The rms scatter between the surface brightness profiles is 0.8% close to the

[2] IRAF 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.

[3] http://www.sdss.org/dr4/algorithms/sdssUBVRITransform.html#Lupton2005

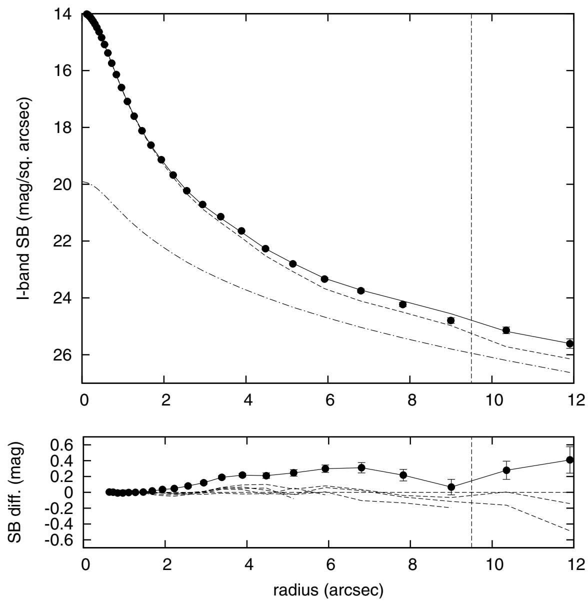

Fig. 2. *Upper panel*: the I-band surface brightness profile of S5 0716+714 (filled symbols). The solid line shows the core + host galaxy model, the dashed line the core component and the dot-dashed line the host galaxy component. The vertical dashed line shows the outer radius of the model-fitting region. *Lower panel*: the surface brightness profiles of S5 0716+714 (symbols and solid line) and stars 2, 3, 5, 6, S1, and S2 (dashed lines) relative to star 5. Each star is traced out to a radius at which the surface brightness can be determined to higher accuracy than 10%.

center and increases to ~10% at the outer fitting radius. Part of this increase is undoubtedly due to the increase in noise in measuring the surface brightness at the faint outer wings of the stars. However, we assume conservatively that the increase is entirely due to PSF variability and represent it by a parabolic expression

$$\sigma_{\rm PSF}(r) = 0.008 + 4 \times 10^{-5} \cdot r^2,$$

where $\sigma_{\rm PSF}(r)$ is the uncertainty in the PSF relative to the intensity at radius r (pixels) from the PSF center. We then compute the expected variance of a pixel σ^2 with intensity I (ADU) and distance r from the center of S5 0716+714 from the expression

$$\sigma^2 = \frac{G * I + R^2}{G^2} + [\sigma_{\rm PSF}(r) * I]^2,$$

where G is the effective gain and R is the effective readout noise, and compute the χ^2 from

$$\chi^2 = \sum_i \frac{(I_i - M_i)^2}{\sigma_i^2},$$

where M is the model intensity and the summation is over all unmasked pixels within the fitting radius.

In addition to the i-band images, two spectra with an exposure time of 900 s were obtained using grism #4 of ALFOSC, which covers the wavelength range 3200–9100 Å. The spectral resolution achieved using the 1.″3 slit was 21 Å. Due to the effect of the secondary spectrum and fringing longwards of 6000 Å, we studied only the wavelength range 4000–6000 Å. The summed spectrum has a signal-to-noise ratio (S/N) of ~250, but the spectrum remains featureless.

Table 1. Model fit results. PSF1 was derived from stars 5 and S1 in Fig. 1 and PSF2 from stars 6 and S2.

Model	PSF	$I_{\rm core}$	$I_{\rm host}$	$r_{\rm eff}$	χ^2/d.o.f.
Core	PSF1	13.74			1.57
Core + De V.	PSF1	13.77	17.47	2.″7	1.31
Core	PSF2	13.73			1.95
Core + De V.	PSF2	13.79	17.09	1.″8	1.41

3. Results

Table 1 indicates the results of the model fits, and the upper panel of Fig. 2 shows the one-dimensional surface brightness profile of S5 0716+714 and the model profiles. The I-band magnitude of the nucleus translates into R ~ 14.2 using $(R - I) = 0.5$ (Gu et al. 2006; Stalin et al. 2006), so the nucleus had brightened by ~0.6 mag in the R-band from the deep minimum on Dec. 17th.

The host galaxy is faint ($I = 17.5$) compared to the nucleus and never exceeds the core brightness at any radius, but is visible as a small excess in the surface brightness profile of S5 0716+714 (see Fig. 2). Since PSF1 was constructed from stars closer to S5 0716+714 than PSF2, it is unsurprising that PSF1 provides a more accurate description of the data (smaller χ^2) than PSF2. The fit with core + galaxy reduces the χ^2 of the fit, but none of the fits provide formally satisfactory fits, most likely due to higher-order PSF variability unaccounted for in our radial PSF variability model.

We completed several tests to ensure that the observed excess is real and not due to PSF variability over the field of view. Firstly, we compared the scaled surface brightness profiles of stars 2, 3, 6, S1, and S2 and S5 0716+714 with the surface brightness profile of star 5 (see the lower panel of Fig. 2). There is a clear excess around S5 0716+714 that exceeds the rms scatter of stellar profiles by a factor of 3–6 at $r > 2''$. The excess is clearly above any PSF variability observed over the field of view.

Secondly, although the fits with PSF2 provide a slightly worse fit than with PSF1, the host galaxy component is still present with similar brightness and effective radius as with PSF1. Also this test indicates that PSF variability does not affect the results significantly. Finally, we fitted core + host galaxy models to stars 6, S2, and S4, which are similar in brightness to S5 0716+714. Using PSF1, the fit converged towards a solution $r_{\rm eff} \rightarrow 0$ in all three cases, i.e. no host galaxy component was detected in targets known to be unresolved. Based on the three test mentioned above, we conclude that the excess around S5 0716+714 is real and we have detected the host galaxy.

Knowing the host galaxy magnitude, we can estimate the redshift of S5 0716+714, albeit with rather large margins. Sbarufatti et al. (2005) demonstrated that the distribution of BL Lac host galaxy absolute magnitude M_R is almost Gaussian with an average of –22.8 and $\sigma = 0.5$, using the same cosmology as we do here, and BL Lac host galaxies can therefore be used as a "standard candle" to estimate distances. Before using their method, we first have to transform the apparent I-band magnitude of the host galaxy to apparent R-band magnitude. We correct the host galaxy magnitude $I = 17.47$ for the galactic absorption by assuming $A_I = 0.06$ (Schlegel et al. 1998). Since the observed $R - I$ color depends on redshift, we have to determine the redshift by iteration, starting from $z = 0$ and using Eq. (2) in Sbarufatti et al. (2005) and typical elliptical galaxy colors from Fukugita et al. (1995). This iteration yields $R = 18.3$ and $z = 0.31$ in the adopted cosmology.

To compute the uncertainty in the derived redshift, we use the difference between the fits with PSF1 and PSF2 as an estimate for the 1σ fitting uncertainty of the host galaxy magnitude, i.e. $\sigma_{I\ \mathrm{host}} = 0.4$ mag. Summing this in quadrature with the error of the zero point (0.2 mag), the total uncertainty in the I-band magnitude of the host is 0.45 mag. Performing the redshift iteration at $I_{\mathrm{host}} + 0.45$ mag and $I_{\mathrm{host}} - 0.45$ mag yields an error of ±0.5 mag in the R-band magnitude of the host and ±0.06 for z. By adding to this in quadrature the inherent uncertainty in the method ($\Delta z = 0.05$, Sbarufatti et al. 2005), we derive the final error in z to be 0.08.

Finally, we mention that the effective radius of the host galaxy $2\farcs7 \pm 0\farcs9$ translates into 12 ± 4 kpc at $z = 0.31$, which is consistent with typical values found for BL Lac host galaxies.

4. Discussion

Our measurement of redshift does not significantly differ from the value $z = 0.26$ obtained for three galaxies close to S5 0716+714 using spectroscopy (Stickel et al. 1993; Bychkova et al. 2006, galaxies G1-G3 in Fig. 1). Both the host galaxy and nearby environment therefore have properties indicative of an object at $z = 0.26$. The nearby companion $4\farcs2$ W of S5 0716+714 remains unresolved in our image.

There have been four previous attempts to derive the host galaxy properties of S5 0716+714 with varying success. Stickel et al. (1993) found the object to be unresolved in a 500 s R-band image obtained under 1.1 arcsec seeing at the Calar Alto 3.5 m telescope. Scarpa et al. (2000) obtained a 614 s HST image through the F702W filter and found the surface brightness profile to be consistent with the PSF and derived an upper limit $R > 20.0$ for the host galaxy. Pursimo et al. (2002) found that S5 0716+714 was unresolved in a 2120 s R-band exposure at the NOT, but the PSF was determined partly from a different image and the PSF shape was uncertain. Finally, Bychkova et al. (2006) reported a detection of excess radiation in the wings of S5 0716+714 in VRI images of exposure times between 600 and 1500 s obtained with the 6 m SAO telescope. They described the excess as very large ($15'' \times 7''$) and elliptical in shape.

Bychkova et al. (2006), hereafter B06, did not perform model fitting to their image but rather derived the host galaxy properties from PSF-subtracted images. Since neither surface brightness values nor the FWHM were provided by B06, it is difficult to assess if the large extent of the host galaxy reported in B06 is consistent with our host galaxy magnitude and effective radius. However, they indicated that $I \sim 15.1$ for the extended emission, far too bright to be consistent with the faint host galaxy that we observe in our i-band image.

The upper limit $R > 20.0$ derived by Scarpa et al. (2000), hereafter S00, may at first glance appear to contradict our estimate for the host galaxy of $R = (18.3 \pm 0.5)$. Based on this upper limit, Sbarufatti et al. (2005) inferred that $z > 0.52$ for S5 0716+714. The brightness of the nucleus of S5 0716+714 was the same in S00 ($R = 14.18$) as here ($R \sim 14.2$), so the difference cannot be explained by a greater core dominance in one of our studies. However, the upper limits in Scarpa et al. (2000) are based on statistical errors and do not take into account possible systematic errors. Consequently, there might be considerable uncertainty in the derived upper limit and the two results could be consistent within errors.

We finally note that our redshift estimate is based on the assumption that the host galaxy of S5 0716+714 has an average luminosity. The failed previous attempts to detect the host galaxy suggest that the host galaxy may actually be below average luminosity and the redshift consequently lower that 0.31. We note that the scatter in the BL Lac host galaxy luminosities is already included in our redshift error since this scatter is included in the 0.05 uncertainty of the method by Sbarufatti et al. (2005). Thus, within a margin of error of 2σ, the redshift could be in the range of 0.15 to 0.47.

5. Conclusions

A deep i-band image of the BL Lacertae object S5 0716+714 acquired at the Nordic Optical Telescope while the target was in an low optical state has enabled us to detect the underlying host galaxy. The host galaxy has an I-band magnitude of 17.5 ± 0.5 and an effective radius of (2.7 ± 0.8) arcsec. Using the host galaxy as a "standard candle" and a method proposed by Sbarufatti et al. (2005), we derive a redshift of $z = 0.31 \pm 0.08$ (1σ error) for the host galaxy of S5 0716+714. This redshift is consistent with the redshift $z = 0.26$ determined by spectroscopy for 3 galaxies close to S5 0716+714. The corresponding effective radius of the host galaxy at $z = 0.31$ would be 12 ± 4 kpc, also consistent with the values obtained for BL Lac host galaxies in other studies. An optical spectrum obtained at the same epoch shows a featureless continuum with no identifiable spectral lines.

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