FURTHER SPECTROSCOPIC OBSERVATIONS OF THE CSL 1 OBJECT

M. Sazhin,1 M. Capaccioli,2,3 G. Longo,2,3,4 M. Paolillo,3,4 and O. Khovanskaya1

Received 2005 June 16; accepted 2005 November 8; published 2005 December 12

ABSTRACT

CSL 1 is a peculiar object (R.A. = 12°23′30.5″, decl. = −12°38′57″ [J2000.0]) that, because of its photometric and spectroscopic properties, is possibly the first case of gravitational lensing by a cosmic string. In this Letter we present additional evidence, based on medium to high resolution VLT+FORS1 observations, that the spectra of the two components of CSL 1 are identical within a confidence level higher than 98% and that the velocity difference of the two components is consistent with zero. This result adds further confidence to the interpretation of the system as a true lens.

Subject headings: cosmological parameters — galaxies: individual (CSL 1) — galaxies: peculiar — gravitational lensing

Online material: color figure

1. INTRODUCTION

As recently stated in the masterly review by Kibble (2004), the last 2 years have seen a renewal of interest in the cosmological role of cosmic strings, after more than a decade of relative quiescence: an interest that was mainly triggered by the discovery of the unusual object CSL 1 (R.A. = 12°23′30.5″, decl. = −12°38′57″ [J2000.0]; Sazhin et al. 2003, hereafter Paper I) in the OACDF (Osservatorio Astronomico di Capodimonte Deep Field; Alcalá et al. 2004) and by the indirect evidence obtained by Schild (2004) from the luminosity fluctuations of the quasar Q0957+561AB.

CSL 1 (see Fig. 1) is a double source lying in a low-density field. In the original images the components, 179 apart, appeared to be extended and with roundish and identical shapes. By low-resolution spectroscopy we learned that both components are at a redshift of 0.46 ± 0.008, and by photometry (both global properties and luminosity profiles) that they match the properties of two giant elliptical galaxies. Detailed analysis showed that the spectra of the two components were identical at a 99.9% level. Such a conclusion, however, was hindered both by the limited wavelength range spanned by the spectra and by their relatively low signal-to-noise ratio (S/N).

As discussed in Paper I, the only possible explanation of the CSL 1 properties is either (1) an unlikely chance alignment of two giant elliptical galaxies at the same redshift and with very similar spectra, or (2) a gravitational lensing phenomenon. But in this second case, due to the lack of asymmetry in the two images, the lens could not be modeled with the standard lensing by a massive compact source. Actually, the usual gravitational lenses, i.e., those formed by bound clumps of matter, always produce inhomogeneous gravitational fields that distort the images of extended background sources (see Schneider et al. 1992; Kochanek et al. 2004). The detailed modeling of CSL 1 proved that the two images were virtually undistorted (see Paper I for details). The only other explanation left in the framework of gravitational lensing theory was that of lensing by a cosmic string.

In Paper I we indicated two possible experimenta crucis: (1) the detection of the sharp edges at faint light levels, since this is the signature expected from the lensing by a cosmic string, and (2) the detection of a small-amplitude but sharp discontinuity in the local cosmic microwave background (Gangui et al. 2002). The first test calls for high angular resolution and deep observations with the Hubble Space Telescope; time has already been allocated but the observations have not yet been performed. The second test was attempted using the preliminary release of the Wilkinson Microwave Anisotropy Probe data (Kaiser & Stebbins 1984; Lo & Wright 2005). By careful processing, a 1σ positive detection at the position of CSL 1 was found. Even though such a detection seems to imply an unrealistic speed of 0.94c for the string, the authors pointed out that both the low angular resolution and the low S/N could prevent the detection of the expected signature.

Another test was proposed by several authors (Vilenkin & Shellard 1994; Hindmarsh 1990; Bernardeau & Uzan 2001; Uzan & Bernardeau 2001; de Laix & Vachaspati 1996), and more recently by Huterer & Vachaspati (2003). It is based on the fact that the alignment of the background object (a galaxy) inside the deficit angle of the string is a stochastic process determined by the area of the lensing strip and by the surface density distribution of the extragalactic objects that are lying behind the string. All the lensed objects will fall inside a narrow strip defined by the deficit angle computed along the string pattern. A preliminary investigation of the CSL 1 field showed a significant excess of gravitational lens candidates selected on the bases of photometric criteria only (Sazhin et al. 2005). Spectroscopic observations are being obtained for a first set of candidates and will be discussed elsewhere.

In this paper we address on firmer grounds the issue of the gravitational lens nature of CSL 1 using intermediate-resolution spectra obtained with the ESO Very Large Telescope (VLT) and FORS1 spectrograph.

2. THE DATA AND DATA REDUCTION

New spectra of CSL 1 were obtained in 2005 March with the VLT5 using the FORS1 spectrograph under Director’s Discretionary Time (proposal 274.A-5039).

5 The Very Large Telescope is operated by the European Southern Observatory and is located at Mount Paranal in Chile; http://www.eso.org/paranal.
The spectra were acquired on 2005 March 15–19 in the FORS1 long-slit configuration 600V+GG435 ($\lambda/\Delta\lambda = 990$ at central wavelength), setting the slit of the spectrograph across the centers of the two components of CSL 1. The observations were split into several exposures, to prevent saturation and to allow for a better removal of the bad pixels and cosmic rays. The risk of cross-contamination between the spectra of the two components was minimized by retaining only the six frames with an average S/N of $\sim 12$ and a point-spread function FWHM of $<1.0''$. For a total exposure time of 4740 s.

During observations a short $R$-band exposure was also obtained to check the pointing of the instrument. Owing to the excellent seeing conditions, this image could be used to test the extended nature and the similarity of the light profiles of the two images. The dot-dashed line (with no data symbols) in Figure 2 shows the light profile of an unresolved star present in the field, compared to the light profiles of the two images of CSL 1, which appear to be clearly resolved and identical within the errors. A de Vaucouleurs fit yields $r/e = 1.6$.

The spectral data were reduced through standard MIDAS procedures, and after bias subtraction, flat-fielding, wavelength calibration, and sky subtraction, the spectra were realigned to correct for dithering and stacked. Since the shift values were set to an integer number of pixels, no resampling was applied, in order not to affect the noise statistics. The stacking was performed using a simple median filter to reject cosmic rays.

The spectrum of each component was extracted using a 5 pixel strip (1 pixel = 0''21) centered on the emission peak with the purpose of maximizing the S/N. In a similar way, the background counts were extracted in two stripes located 40 pixels from each component in order to measure the local background while minimizing the contribution from the source. The error on the spectral counts was calculated with the expression

$$\sigma(\text{ADU}) = \sqrt{\sigma_{\text{bkg}}^2 + \frac{N(\text{ADU})}{n_{\exp} \times g}},$$

where $N(\text{ADU})$ are the source counts measured along the spectrum, $n_{\exp}$ are the number of median-averaged exposures, $g$ is the instrumental gain, and $\sigma_{\text{bkg}}$ represents the background rms measured over $5 \times 20$ pixels centered at each wavelength. By folding the images we estimate an average cross-contamination of $7\% \pm 1\%$. The resulting spectra and their ratio are shown in Figure 3. No flux calibration was applied to the data. It has to be stressed that the narrow spikes visible in the figure are residuals left after the removal of bright sky lines.

The spectra of the two components turned out to be identical at visual inspection. In fact, Pearson, Spearman, and Kendall correlation tests indicate correlation coefficients of 0.96, 0.94, and 0.94, respectively, with a significance of $>99.9\%$ in all cases. The degree of similarity was further quantified by running a $\chi^2$ test both on the whole wavelength range and on the most prominent spectral absorption features, namely, the Ca II (H and K), H$\beta$, H$\delta$, and H$\gamma$ lines and the G band. The test yields $\chi^2 = 1.03$, implying that the two spectra are consistent within $<2\sigma$ (80\%); we also compared the distribution of the observed differences to the frequencies expected in the case of pure Gaussian noise, finding that the two are consistent at the 95\% level and that there is no deterministic part in the residuals. An even better agreement (1 $\sigma$) is found for the individual absorption features. To further check whether the observed consistency can be due to the known similarity of early-type

---

6 The point-spread function represents the image of a pointlike object. Its FWHM measures the level of blurring due to atmospheric and instrumental factors.

7 The regions affected by sky line subtraction residuals were excluded from the test.
galaxies, we repeated the test on a sample of spectra extracted from the SDSS\(^8\) luminous red galaxies, chosen to have a redshift difference and S/N comparable to the CSL 1 data. We performed 2000 comparisons, obtaining that <2% of the examined SDSS spectra are as consistent as the spectra of the two CSL 1 components.

A cross-correlation test based on the spectral lines mentioned above yields a velocity difference between the two components of \(\Delta v = 14 \pm 30\) km s\(^{-1}\). However, if we exclude the H\(\beta\) line, which is affected by residual instrumental effects, this figure reduces to \(0 \pm 20\) km s\(^{-1}\).

3. CONCLUSION

The similarity of the spectra of the two components of CSL 1 and the zero velocity shift between them strongly support the interpretation of CSL 1 in terms of gravitational lensing. The data obtained so far do not allow us to completely rule out the possibility of a chance alignment of two giant elliptical galaxies, but the new data presented in this Letter make such an alignment very unlikely. In the case of chance alignment, in fact, the two images of CSL 1 would correspond to two giant ellipticals with identical shapes and spectra, placed at the same redshift. The probability of finding two ellipticals of \(M_\text{pR} = -22.3\) within 2\" (20 kpc) and with a radial distance <1 Mpc (2 \(\sigma\) upper limit) is \(P \sim 1.5 \times 10^{-15}\), accounting for clustering effects (e.g., Zehavi et al. 2005).\(^9\) Integrating over the volume sampled by the OACDF for a galaxy of the same magnitude as CSL 1, we calculate that we expect to find \(\sim 9 \times 10^{-4}\) pairs in the whole survey. Including the spectral similarity, we obtain an upper limit of \(P < 2 \times 10^{-5}\). As was already mentioned in Paper I, this could still be explained if CSL 1 belonged to a rich cluster with two central dominant galaxies, but this is not the case. Careful inspection of the CSL 1 field shows in fact that it is a rather isolated object with no other nearby galaxies of comparable brightness; furthermore, the velocity difference measured between the two spectra is much smaller that the one expected in a rich cluster (\(\Delta v \sim 300\) km s\(^{-1}\)).

In the gravitational lensing scenario, as already stated in Paper I, the observed phenomenology cannot be understood in terms of lensing by compact clumps of matter such as, for instance, a singular isothermal sphere model or any other model listed in C. R. Keeton’s lens modeling software (Kochanek et al. 2004). The only possible type of lens that can produce a morphology similar to that observed in CSL 1 seems to be a cosmic string (Paper I).

Lensing by a cosmic string seems capable of explaining all the observational evidence gathered so far and deserves further investigation. Cosmic strings were predicted by Kibble (1976), and their role in cosmology has been extensively discussed by Zel’dovich (1980) and Vilenkin (1981). Recent work (Kibble 2004; Polchinski 2004; Davis & Kibble 2005) has also shown their relevance for both fundamental physics and cosmology. In particular, it has become apparent that the detection of a cosmic string would lead to a direct measure of the energy scale of symmetry breaking in grand unified theories. If we assume that CSL 1 is produced by a cosmic string, its measured properties would imply a linear density of the string of order \(G_\mu \approx 4 \times 10^{-7}\) and a corresponding grand unified theory energy scale of \(\sim 10^{15}\) GeV (Kibble 1976; Eidelman et al. 2004\(^10\)).

\(^{8}\) Sloan Digital Sky Survey, data release 4; http://www.sdss.org.

\(^{9}\) \(P = \int_{v_1}^{v_2} N_{\text{gal}}[1 + \xi(v)] \, dv_1 \, dv_2\), where \(N_{\text{gal}}\) is the space density of elliptical galaxies, \(\xi(v)\) is the galaxy correlation function, \(V_1\) is the volume enclosing the two galaxies, and \(V_2\) is the volume of the survey.

\(^{10}\) Available on the Particle Data Group World Wide Web site at http://pdg.lbl.gov.

---

**Fig. 3.**—Top: Spectra of the two components of CSL 1. Bottom: Ratio between the two spectra in the top panel. The 1 and 3 \(\sigma\) limits are shown as dark and light gray shaded regions. [See the electronic edition of the Journal for a color version of this figure.]
Hopefully, the question of the nature of CSL 1 will soon be answered by our Hubble Space Telescope observations approved in Cycle 14 to carry out the test proposed by the authors in Paper I and which will allow us to verify the cosmic string hypothesis on firmer grounds.

M. V. Sazhin acknowledges the INAF–Capodimonte Astronomical Observatory for hospitality and financial support.

O. Khovanskaya acknowledges the Department of Physics of the University Federico II in Naples for financial support. The authors wish to thank C. Cezarsky, Director General of the European Southern Observatory, for allocating Director’s Discretionary Time to this project. The work was also supported by the Russian Fund of Fundamental Investigations No. 04-02-17288. We thank the anonymous referees for the helpful suggestions.

REFERENCES

Alcalá, J. M., et al. 2004, A&A, 428, 339
Bernardeau, F., & Uzan, J.-P. 2001, Phys. Rev. D, 63, 023005
Davis, A.-C., & Kibble, T. W. B. 2005, Contemporary Physics, 46, 313
de Laix, A. A., & Vachaspati, T. 1996, Phys. Rev. D, 54, 4780
Eidelman, S., et al. 2004, Phys. Lett. B, 592, 1
Gangui, A., Pogosian, L., & Winitzki, S. 2002, NewA Rev., 46, 681
Hindmarsh, M. 1990, in The Formation and Evolution of Cosmic Strings, ed. G. Gibbons, S. W. Hawking, & T. Vachaspati (Cambridge: Cambridge Univ. Press), 527
Huterer, D., & Vachaspati, T. 2003, Phys. Rev. D, 68, 041301
Kaiser, N., & Stebbins, A. 1984, Nature, 310, 391
Kibble, T. W. B. 1976, J. Phys. A, 9, 1387
———. 2004, preprint (astro-ph/0410073)
Kochanek, C. S., Falco, E. E., Impey, C., Lehar, J., McLeod, B., & Rix, H.-W. 2004, CASTLES Survey (Cambridge: CfA), http://cfa-www.harvard.edu/castles
Lo, A. S., & Wright, E. L. 2005, preprint (astro-ph/0503120)

Polchinski, J. 2004, in AIP Conf. Proc. 743, The New Cosmology, ed. R. E. Allen, D. V. Nanopoulos, & C. N. Pope (New York: AIP), 331
Sazhin, M. V., Khovanskaya, O. S., Capaccioli, M., Longo, G., Alcalá, J. M., Silvotti, R., & Pavlov, M. V. 2005, Astron. Lett., 31, 73
Sazhin, M. V., et al. 2003, MNRAS, 343, 353 (Paper I)
Schild, R., Masnyak, I. S., Hnatyk, B. I., & Zhdanov, V. I. 2004, A&A, 422, 477
Schneider, P., Ehlers, J., & Falco, E. E. 1992, Gravitational Lenses (Berlin: Springer)
Uzan, J.-P., & Bernardeau, F. 2001, Phys. Rev. D, 63, 023004
Vilenkin, A. 1981, Phys. Rev. D, 23, 852
Vilenkin, A., & Shellard, E. P. S. 1994, Cosmic Strings and Other Topological Defects (Cambridge: Cambridge Univ. Press)
Zehavi, I., et al. 2005, ApJ, 630, 1
Zel’dovich, Ya. B. 1980, MNRAS, 192, 663