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Letter to the Editor

Discovery of a luminous giant arc in a high redshift cluster of galaxies*

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Abstract. We report the discovery of a bright, R=19.5, arc-like feature associated with a rich cluster of galaxies at a redshift of z=0.56, found in the course of a programme of optical identification of powerful ultra-steep spectrum radio sources at high redshifts. The redshift of this nearly straight arc, z=1.116, implies that the feature is the gravitationally lensed image of a background galaxy. The morphology of the arc, its emission line spectrum and blue colour, and its extremely high surface brightness indicate that the lensed galaxy is likely to be a luminous starburst galaxy, probably a merger of two late type systems. The new arc is the brightest and one of the most distant giant arcs discovered to date, and the only spectroscopically confirmed arc known to be lensed by a cluster at $z > 0.5$.

Key words: Clusters of galaxies; gravitational lensing; arcs

1. Introduction

Tyson *et al.* (1990) and Fort (1991) have advocated the use of rich high redshift clusters of galaxies as gravitational telescopes. The basic idea is that the properties of distant field galaxies can be studied in considerable detail by observing their images lensed gravitationally by rich clusters. This idea is particularly attractive for cosmology since some controversial questions such as the mean redshift of the dense population of blue galaxies that is revealed in very deep images (Tyson 1988; Cowie *et al.* 1991) can, in principle, be addressed by observing arcs towards rich clusters of galaxies at different redshifts. Conversely, the study of faint lensed images in rich clusters can be used to trace the distribution of (dark) matter in these systems (Tyson *et al.* 1990).

Until recently, the number of clusters showing arcs has remained relatively small: about 20 clusters of which about 10 showed giant arcs (Fort, 1991). According to Lynds and Petrossian (1989) about 8% of all clusters with redshifts between 0.2 and 0.4 show arcs. However, giant arcs seem to be more common among X-ray selected clusters, presumably because mostly clusters with deep gravitational potentials are selected (Luppino and Gioia, 1992), but the statistics are still not large enough to be compared with the percentages given by Lynds and Petrossian. The most distant cluster for which a giant arc has been found has a redshift of z=0.583 (Luppino and Gioia, 1992) while the most distant cluster for which faint arcs have been reported has z=0.46 (Tyson *et al.* 1990).

In this *letter* we report the discovery of an extremely luminous arc in a very rich cluster of galaxies at a redshift of z=0.56. The morphology of the arc, its location in the cluster, and its redshift of nearly twice that of the cluster show that the feature is the gravitational image of a distant galaxy. The newly found gravitational arc is the brightest and one of the most distant giant arcs known.

2. Observations

The arc was discovered during a programme of optical identification of the Ooty sample of optically faint radio sources with ultra-steep radio spectra (Gopal Krishna *et al.* 1992). The Ooty occultation radio source, US2236–04, was identified with the first ranked galaxy of an extremely rich cluster (which we will call CL2236–04).

Detailed observations of the arc have been obtained in two runs with the 3.6 m telescope at La Silla. The first observations were obtained in December 1991 using EFOSC1 equipped with a TEK512 CCD that gives a pixel size of 0.61″.

Figure 1 presents a 34 min composite V+R image of the arc. The arc has a total length of 7″ and its width is unresolved in this image that has a seeing of 1.1″. The arc is almost straight and is remarkably close to the second ranked galaxy in the cluster (about 4″). It shows a double morphology with the two components having closely identical angular size and brightness. Photometry of the galaxies near the arc, and of the arc itself was performed on the V and R images obtained with EFOSC1. The photometry was tied to the standard system via observations of two Landolt equatorial standards observed at airmasses similar to the cluster. Considering photon statistics, variable extinction driven by Pinatubo soot, and transformation to the standard system, we estimate the photometry to have an uncertainty of $\pm 0.1^m$.

*Based on observations collected at the European Southern Observatory, La Silla, Chile.

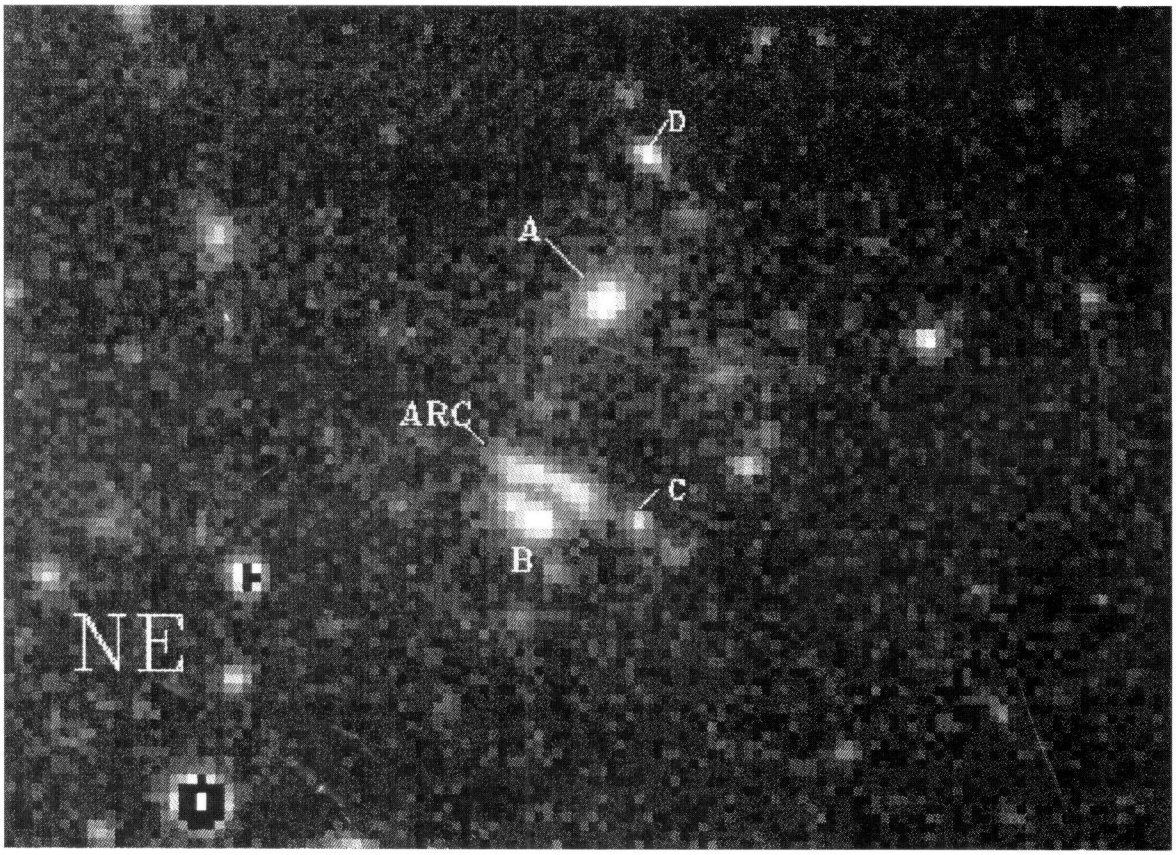

Fig. 1. A composite of V and R frames of CL2236–04. The labeled galaxies are those for which redshifts have been measured.

Table 1 gives the observed magnitudes and colours for the objects measured. The ultra-steep spectrum radio source corresponds to galaxy A in Figure 1.

Table 1. Photometry and redshifts

Object	V	V - R	z
A	20.7	1.6	0.552
B	20.9	1.5	0.558
C	22.4	1.4	0.560
D	21.9	1.2	0.556
Arc	20.4	0.9	1.116

EFOSC1 was also used in spectroscopic mode to obtain a 35 min spectrum of the brightest cluster galaxies. We used the B300 grism which covers the spectral range between 3800Å and 6750Å at 6.3Å/pix. The 1.5″-wide slit was aligned to cover the galaxies marked A, B, and D in Figure 1 as well as a portion of the arc. The resulting spectra corrected for instrumental effec's are shown in Figure 2, and the redshifts of the three galaxies are given in Table 1. No spectral features were detected in the spectrum of the arc, but the spectral energy distribution was found to be much bluer than that of the cluster galaxies.

The spectrum of the arc was obtained with EFOSC1 in July 1992 using the R300 grism (spectral coverage: 5950Å to 9900Å; 7.8Å/pix), which was chosen to match the expected redshift of $z \sim 1$. Six exposures were obtained adding a total exposure time of 5.2 hrs. The 2″-wide slit was oriented at PA=115° to include the whole arc and the galaxy labeled C on Figure 1. Figure 3 shows a reproduction of the median spectrum after sky subtraction showing the presence of a prominent emission line close to 7890Å, and a weaker feature near 9180Å. The 7890Å feature is visible in all 6 spectra, but the weaker line is only visible in the coaded spectrum. Figure 4 shows a tracing of the spectrum of the arc. The spectrum of galaxy C is shown in Figure 2. The redshift of the arc derived from the [OII] and Hγ lines is $z = 1.116 \pm 0.001$.

It is interesting to note that the spectrum of the arc is roughly similar to the spectrum of the straight arc in A2390 reported by Pello *et al.* (1991). In fact, as is the case for A2390, our newly discovered arc also shows velocity structure. This is shown in Figure 5 where the velocities derived from the [OII] and Hγ lines are presented separately. The spectrum was binned in the spatial direction to increase the S/N ratio. The similar velocity structure derived for the two lines confirms the reality of the Hγ line which, at a redshift of z=1.116, falls in a region of the spectrum which is free from strong night sky emission lines.

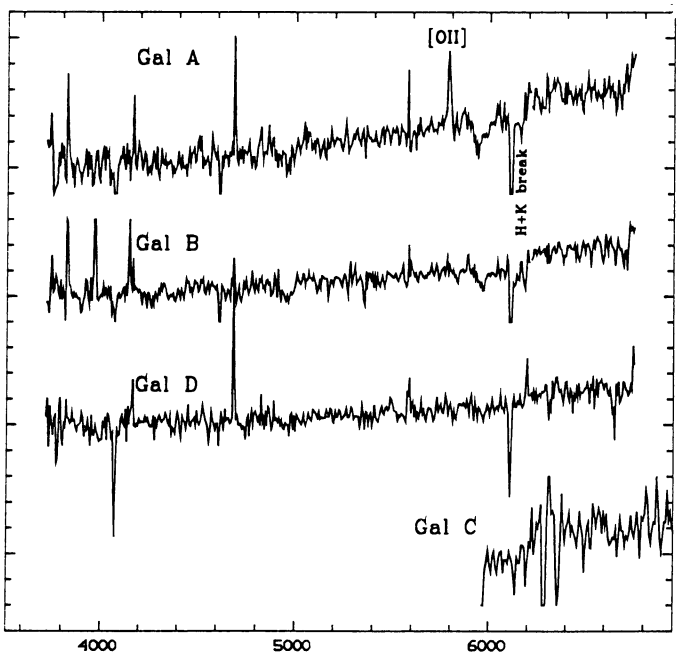

Fig. 2. Tracings of the EFOSC1 spectra of the 4 observed galaxies in CL2236-04. Galaxies A,B, and D were observed with grism B300. Galaxy C was observed with R300. The spectral features used to compute the redshifts are indicated.

3. Discussion

CL2236–04 is a rich compact cluster dominated by a central cD galaxy showing optical emission lines and powerful radio emission. Contrary to what is generally observed in *optically selected* clusters at high redshifts, the brightest galaxies in CL2236–04 are not overbright, although this is also the case for CL0302+1658 at z=0.424 (Mathez *et al.* 1992).

The arc in CL2236–04 is the brightest arc known and the lensing cluster is the second most distant cluster with a giant arc known. The length and the blue colour of the arc are reminiscent of the other known giant arcs (e.g. Hammer, 1991). Spectacularly, however, the arc is brighter in V compared to even the two dominant galaxies in the cluster and its surface brightness, $\mu_V \sim 22.6$ mag/arcsec^2 is brighter than any known arc. This, and the blue colour of the arc, indicate that the lensed object must be a very luminous late type galaxy. The morphology of the arc, its spectrum, and its "rotation" curve suggest that the lensed galaxy may be a merger. In fact, a comparison between the spectrum of our arc, and that of the arc in A2390 which also has a high redshift (z=0.91; Pello *et al.* 1991), shows that our arc has a significantly shallower break at 4000Å, indicating the presence of a young stellar component. Also the large equivalent width of [OII], $\sim$ 120Å, and the [OII]/Hγ ratio are within the range observed for starburst galaxies (Terlevich *et al.* 1991). Therefore, there is substantial evidence that we are seeing a merger starburst galaxy lensed by the cluster. We remark, however, that a quick simulation kindly made by Yannick Mellier using the Toulouse simulation program indicates that the morphology of the arc can also be explained as due to the properties of the lensing potential.

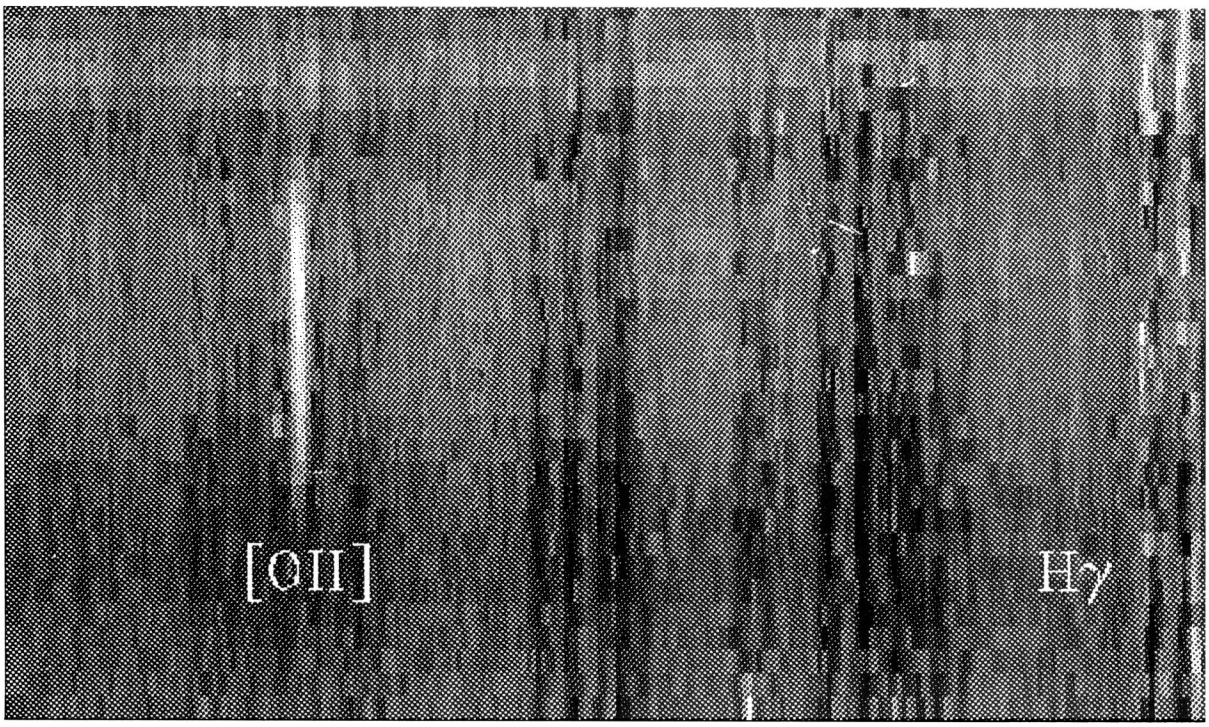

Fig. 3. Median of the 6 EFOSC1 exposures of the arc after sky subtraction. The total exposure time is 5.2 hours. The velocity structure of the arc can be clearly seen in the [OII] line.

More detailed modeling, such as that undertaken by Kassiola *et al.* (1992) for A2390 would be very interesting to place tighter constraints on the properties of the lensed galaxy.

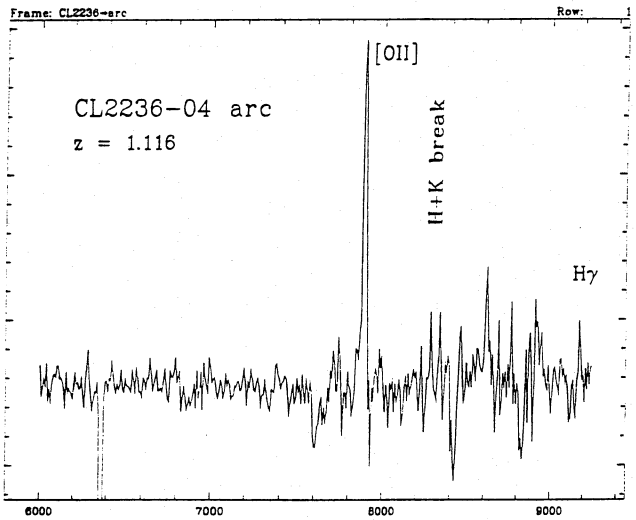

Fig. 4. Tracing of the arc spectrum showing the identified spectral features. Notice that while clearly present, the 4000Å break is much weaker than is observed in normal galaxies, indicating the strong presence of a young stellar population in the lensed galaxy.

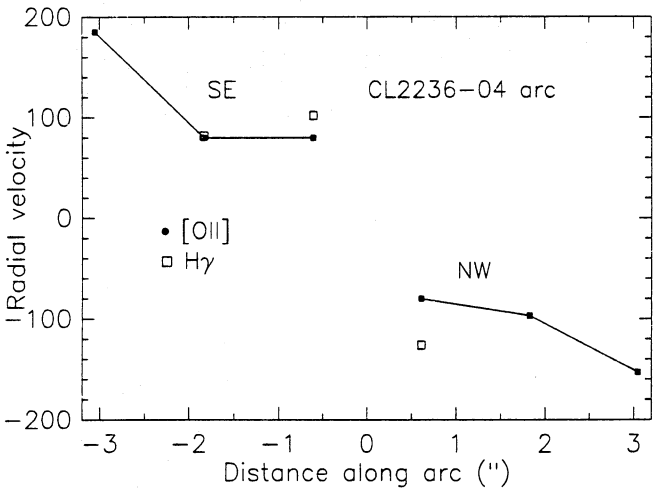

Fig. 5. Velocity structure of the CL2236-04 arc. The radial velocities derived from [OII] and Hγ are plotted separately.

Given that the redshift and the richness of the lensing cluster are both very high, deeper imaging of the region should reveal several blue arcs and arclets similar to those found towards less distant clusters, if indeed a rich population of field galaxies exists at redshifts of $z > 1$, as has been proposed by Tyson and collaborators (Tyson 1988; Guhathakurta *et al.* 1989). This work is in progress.

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