Discovery of the First Gravitational Einstein Ring: the Luminous Arc in Abell 370

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Since the discovery of the first luminous arcs in rich clusters of galaxies (Soucail et al., 1987a, Lynds and Petrossian 1987), several hypotheses were suggested to explain their nature and origin. One of them is the gravitational lensing of a background galaxy nearly perfectly aligned with the deflector (in this case the cluster core) and the observer. A piece of evidence for this effect comes from our observations of such a structure in the distant cluster Abell 370 (z = 0.374). We first attempted to get a spectrum of the eastern end of the arc in this cluster during an observing run at ESO in November 1986 (Soucail et al., 1987b). In fact, bad weather conditions only allowed a one-hour exposure on this object leading to a poor S/N spectrum. Nevertheless, in view of the spectral energy distribution we suggested that this could result from a background galaxy at a redshift of 0.6. Moreover, our recent spectroscopic data on the quite similar blue arc in the cluster Cl 2244-02 (z = 0.329) have shown that the spectral energy distribution is flat and consistent with the one of a distant object (galaxy or quasar). This is also in favour of the gravitational lensing model.

Even though the gravitational lensing appeared to be a very attractive model this had to be confirmed with better data than the one obtained in A370 for two reasons:

(1) the spectrum we obtained is very faint and the redshift had to be confirmed;

(2) some astronomers were not convinced that the eastern part of the structure really belongs to the arc, in spite of a similar surface brightness in each bandpass.

This is the reason why we reobserved intensively the arc of A 370 on October 18-22, 1987 at ESO with EFOSC/PUMA 2 at the 3.6-m telescope.

For this peculiar object we used a long slit but we also used the PUMA 2 system (Fort et al., 1986) to punch curved slits well suited to the geometry of the arc. This has the advantage of collecting the maximum of energy through the aperture plate and to obtain at the same time the redshifts of the galaxies located near the ring structure. Sky subtraction was ensured by using a duplicate curved slit punched on the same mask close to the arc. The B 300

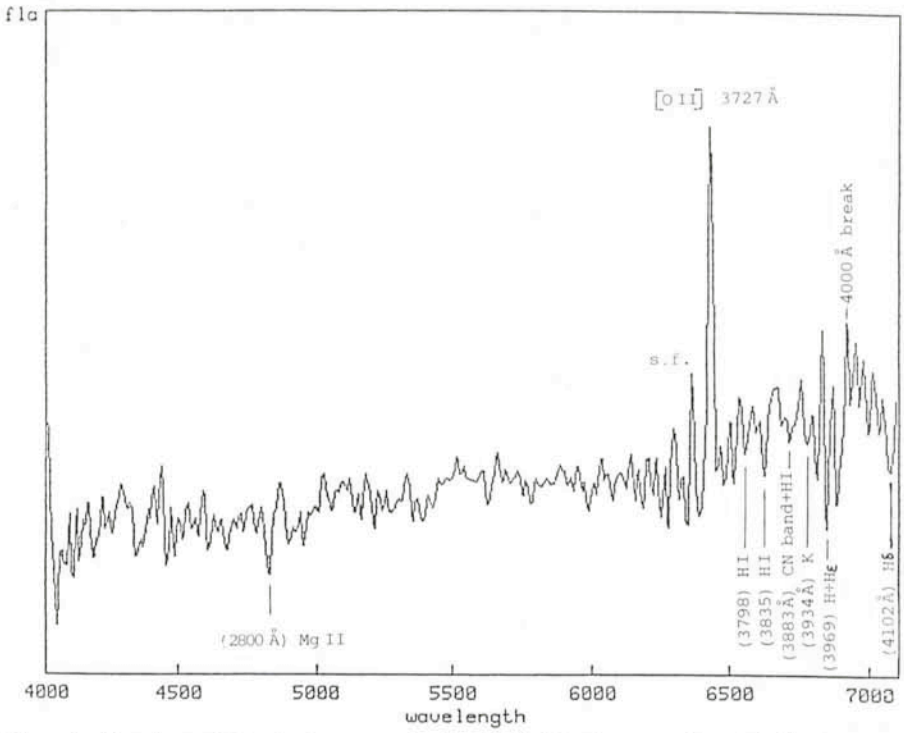

Figure 1: *Spectrum of the luminous arc in Abell 370. The lines mentioned in the text are indicated. ESO 3.6 m + EFOSC, 6 hours integration.*

grism used gave a resolution of 15 Å over a spectral range from 3800 Å to 7500 Å. Several 90-min. exposures were made leading to a total integration time of 4h30 with the curved slit and 1h30 with the long slit. We then compensated the rather high read-out noise of the RCA CCD (60 e⁻ r.m.s.) by co-adding the total 6 hours exposures. Thanks to these data we can now con-

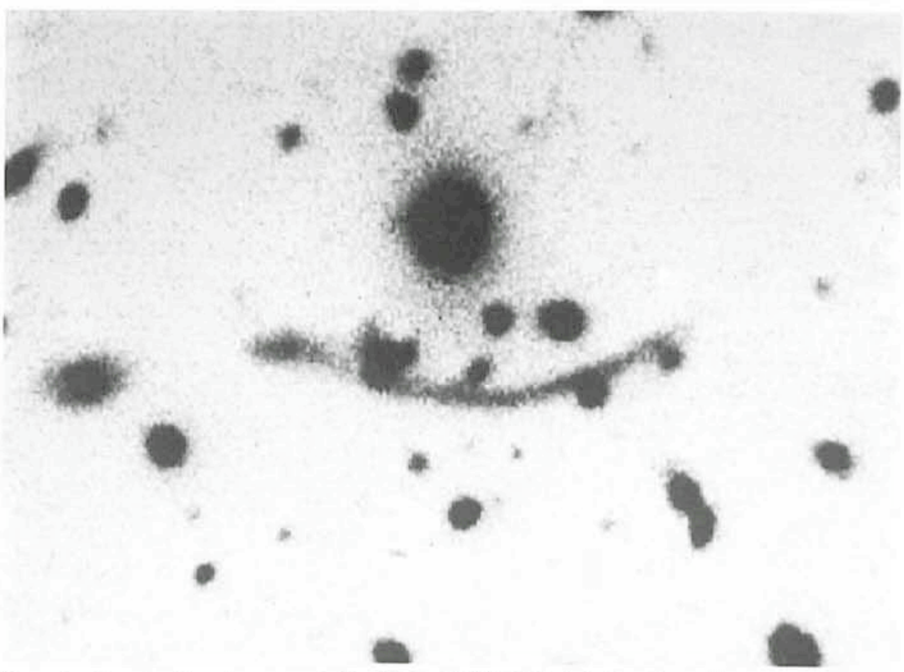

Figure 2: *The giant luminous arc in Abell 370. CFHT, 0."2/pixel, 10 min., seeing 0."7, November 25, 1986.*

firm that both the central and the eastern parts of the arc really present the same spectral energy distribution: therefore it is now proved that the eastern end of the structure belongs to the arc!

Moreover, a narrow emission line is clearly observed at 6427 Å all along the arc spectrum. The assumption that it is the [O II] λ 3727 line leads to a redshift z = 0.724, a value confirmed by the detection of absorption features corresponding to the Ca II λλ 3933, 3968 Å and the 4000 Å break, the CN band at 3883 Å, the MgII λ 2800 Å line and several Balmer lines, all at the same redshift. These features are typical of a blue galaxy, redshifted at z = 0.724.

A complete discussion of these data is out of the scope of this paper and will be presented in a letter to *Astronomy and Astrophysics*. Nevertheless it is obvious now that all these results confirm that the arc in A 370 does result from the gravitational lensing of a background galaxy at a redshift of 0.724. With respect to the model presented by Soucail et al., (1987 b) the only difference is that the mass of the lens is lowered by a factor of 1.30.

It is clear that the observations of such giant arcs in distant clusters of galaxies will open new fields of investigation for gravitational lensing phenomena with probably important consequences on observational cosmology to study the distribution of dark matter in the universe.

In particular, one can imagine to use the rich clusters of galaxies as "gravitational telescopes" to search for more distant objects in the universe (Nottale and Hammer, 1984).

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Lunar Occultations at La Silla

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1. Introduction

Lunar occultations provide the means to obtain high angular resolution down to the milliarcsecond level in the optical and near infrared spectral regions, by analysing the diffraction pattern produced when a source disappears behind (or reappears from) the limb of the Moon. This technique has its main application in the measurement of angular diameters of stars. In particular, it is noteworthy to stress that the majority of all known angular diameters have been measured in this way – see for instance the reviews by McAlister, 1985 and White and Feierman, 1987. In fact, a resolution of one milliarcsecond (mas) at $\lambda = 1 \div 3\ \mu m$ is far beyond the possibilities of any other available technique, at present and what can be foreseen in the immediate future (with the possible exception of future long-baseline Michelson interferometry).

In June 1987, observations in the near infrared of lunar occultations were performed at La Silla. The programme – proposed by A. Richichi (ESO), F. Lisi and P. Salinari (Arcetri Observatory, Italy) – had several goals. First of all, our knowlege of the relation between temperature (easily obtained if the diameter and the total flux are known) and spectral type for cool stars is still largely unsatisfactory. According to a review by J. Davis until 1984 there were only 32 stars with a diameter known at the 5 % level or better – the minimum for a useful check of current theories with observations – and many of them were early-type stars or cool supergiants. Therefore, we felt that if observations with the instrumentation at La Silla proved feasible, one could hope to significantly improve in the set of measured diameters by observations of occultations in the low-declination portion of the zodiacal belt. This area is very rich of cool giants, especially in the Sagittarius-Scorpius region. In addition, preceding work at the Infrared Telescope of the Gornergrat Observatory (TIRGO), had shown that occultations could also lead to the discovery of compact circumstellar structures (Richichi et al., 1987); therefore many objects in our sample were selected with this aim. Finally, the high resolution provided could lead to serendipitous discoveries, such as the detection of close binaries.

2. The Observations

We travelled to La Silla with a set of about 30 sources that were due to be occulted in a three-night period (10–12 June 1987). They had been selected, not only on the basis of their expected angular diameter being at reach of the technique, but also because of their visual and infrared colours indicating the possible presence of circumstellar dust. They included sources from the SAO, TMSS, IRAS, AFGL catalogues and others. Since most of them had no published data regarding their near-infrared fluxes and/or are strongly variable, we did photometry in the standard J, H, K, L, M broad band filters and in some cases also with the narrow-band circular variable filters (CVF) and in the 10 μm spectral region with the bolometer. Also, for many of the sources it was necessary to determine an accurate position because the error on the given coordinates was often too large. All these preliminary observations were accomplished during a preceding 6-night period at the 1.0-m telescope. They allowed us to move to the 3.6-m for the occultation period with a selected list of "best objects", but they also produced data on many poorly studied objects and revealed some interesting peculiarities.

The observations were carried out at the 3.6-m, using the infrared speckle detector and the Fast Photometry data acquisition programme. This configuration has several advantages: it allows to perform observations at 1 kHz rates with a relatively strong signal, to use the near-infrared filters, and finally to perform also speckle interferometry during the intervals between successive occultations. The fast sampling is necessary because typically all of the critical information is encoded in the central 0.1 ÷ 0.3 seconds of an occultation event. Also the advantage of operating in the near infrared, rather than in the optical, is crucial; the event is slower (roughly by a factor of two), the sources often have their peak emission at wavelengths around 1 μm, and – last but not least – the background level is much lower, because it is mainly composed of scattered sunlight (λ^{-4} law).

Finally, we also had the possibility of a quick switch from Fast Photometry mode to Speckle mode, allowing to collect interferometric data on the same sources that were to be occulted: this means to merge information at the 1-50 mas angular scale of the occultation technique with that at the 0.1-1 arc-