our understanding of the kinematics of the local Universe will be improved.

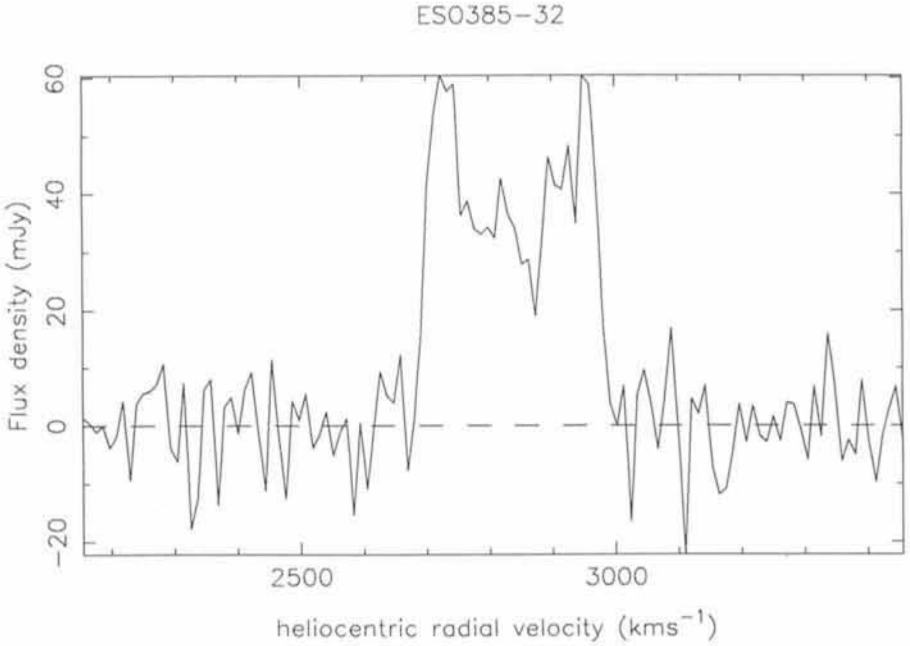

Figure 5: *HI line profile of ESO galaxy ESO 385-G32 detected with the Nançay radio telescope.*

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PROFILE OF A KEY PROGRAMME

Arc Survey in Distant Clusters of Galaxies

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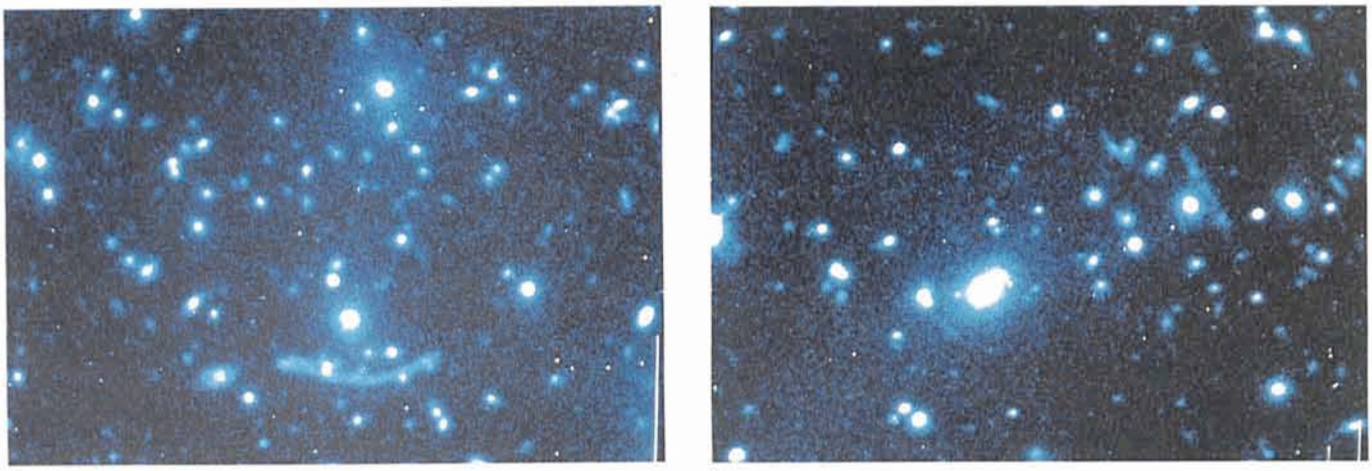
First Steps in the Study of Luminous Arcs

The first luminous arcs were discovered in the centres of rich clusters of galaxies by Soucail et al. (1987) and Lynds and Petrosian (1986). The redshift of the giant arc in Abell 370 ($z = 0.725$) was finally measured with EFOSC/PUMA at the ESO 3.6-m telescope in October 1987 (Soucail et al., 1988). It definitively confirmed that they were gravitationally distorted images of background galaxies by clusters of galaxies (Fig. 1).

During the same period, Tyson (1988) obtained ultra-deep CCD photometry in a sample of empty fields and detected a numerous population of very faint galax-



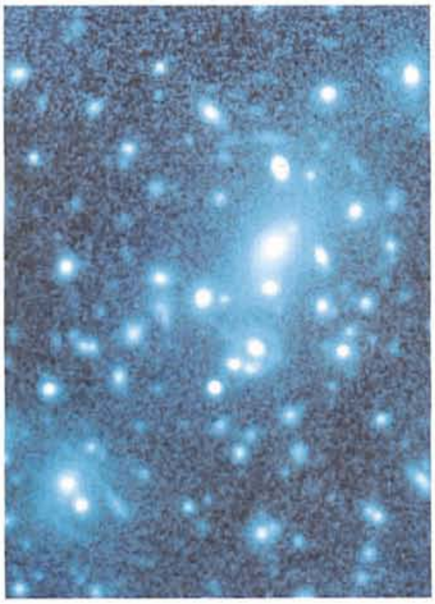
A

B

Figure 1: *Images of the most spectacular cases of arcs and arclets already observed: A. The giant arc in A370: $z_{cluster}=0.374$, $z_{arc}=0.725$ (CCD image from the Canada-France-Hawaii Telescope).*

B. The "straight arc" in A2390: $z_{cluster}=0.232$, $z_{arc}=0.913$ (CFHT image).

C. The complex system of arcs and arclets in the centre of the cluster A2218: $z_{cluster}=0.171$ (CCD image from Calar Alto, Spain).



C

ies. From their blue colour, the low surface brightness and the number counts, he concluded that these objects are most probably distant galaxies with a mean redshift between 1 and 3.

Fort et al. (1988) finally noticed several small tangentially elongated structures in the cluster-lens A370 which were named "arclets" with reference to the giant arcs. These arclets were immediately interpreted as gravitational images of other distant sources, the cluster acting as a lens for all the background objects. The comparison of their blue colour index ($B-R\simeq1$) with evolutionary models of galaxies supported the hypothesis of galaxies at redshift about 1, also consistent with the formation of distorted arclets in a cluster at $z=0.374$.

Although the arcs and Tyson's blue population were independent discoveries, it appeared that they could together open a new and fruitful field of investigation in observational cosmology. No more than 3 years after the first discovery of giant arcs, we are ready to start an extended survey of clusters of galaxies and to take advantage of the new opportunities offered to us by the use of these giant "natural telescopes".

The "Arc Survey": Observational Strategy

Up to now, about 10 large arcs, whose brightness is about one tenth of the sky brightness, have been identified in rich clusters and more than 50% of them have a measured redshift. For example the redshift of the giant arc in C12244-02, obtained after about 15 hours of integration time, is $z=2.238$ and corresponds probably to the most distant field galaxy observed up to now (Mellier et al., 1991, see Fig. 2). The frequency of discovery of luminous extended arcs is now smaller and probably many of the brightest ones have already been observed. On the other hand, the faint arclets are much more regularly found in rich clusters. However, the price to detect them is to do photometry at a surface brightness level of $\mu_B>28$ to 28.5, corresponding to the brightness of most of the galaxies of Tyson's population. Under this condition, and if the background sources are indeed at large redshift (an assumption that we should further be able to check properly) we should find up to 50 arclets per cluster in the most favourable cases (Tyson et al., 1990): rich clusters at intermediate redshift (0.2–0.4) with intense X-ray emission.

In practice, with the 20 nights allocated on the NTT for this ESO Key Programme, and considering the long exposure times necessary to reach the faint levels required to detect the arclets (3 to 4 hours per filter per field, segmented in about 50 randomly shifted exposures of 300 sec. each), we expect to survey 15 clusters with redshift between $z=0.15$ and 0.8 in 3 photometric bands (B, R and I). We refer to the report of a preliminary run we had on the NTT in January 1990 with the TH 1024×1024 CCD to demonstrate the feasibility of such a programme. The survey is strongly supported at CFHT and benefits from a collaboration with T. Tyson and his collaborators on American telescopes (CTIO, KPNO) in order to build up, through a joint international effort, a comprehensive and homogeneous data base of "cluster-lenses" for statistical analysis of the arclets' distribution.

Moreover, a side-observing programme was initiated in collaboration with the University of Barcelona, with access to the William Herschel Telescope in the Canarian Islands (R. Pello, B. Sanahuja) and the University of Durham, with access to UKIRT in Hawaii (R. Ellis and collaborators) to study an unbiased sample of distant magnified galaxies ($z=0.8$ to 2.5) which are intrinsically fainter by one or two magnitudes compared to the present-day deepest spectroscopic surveys (Cowie et al., 1990, Mellier et al., 1991).

Mapping the Dark Matter in Clusters of Galaxies

It is well known from observations of multiple QSOs that the deviation angle due to the gravitational lensing by a typical galaxy of 10^{11} $M_\odot$ is of the order of a few arcseconds. For a cluster of galaxies with a velocity dispersion larger than $\sigma=1000$ km/s the distorted images (whose size depends on σ^2) fall inside a radius of typically 1 arcminute around the cluster centre, a size comparable with the cluster core radius at intermediate redshift.

After the first redshift measurement of the giant arc in A370, it immediately followed that the mass responsible for the large arcs corresponds to $M/L_R \sim 90$ for the cluster. It was a confirmation of the guess that at least 90% of the matter is unseen in rich clusters of galaxies. The evaluations of masses and dark matter distribution from lensing are independent and complementary to other dynamical methods such as the virial theorem (which is questionable in some clusters) and constitute a new powerful tool for mass diagnostics over large scales, provided we are able to constrain the parameters by a statistical study of clusters.

Two main approaches are used simultaneously for the modeling of the arcs. First, since giant arcs are located on the critical lines of the image plane, it is possible to constrain the cluster potential using the position and the shape of the largest arcs (Kochanek et al., 1989). However such models suffer from a large number of free parameters, usually larger than those observable. The redshift of the arcs is essential though not sufficient to limit the space of the solutions since it only fixes the linear scales of the problem. For such an approach, high resolution imaging in good seeing conditions is particularly important because it can strongly constrain the shape of the source and the cluster potential. Due to the large tangential magnification effect, image reconstruction can provide a super resolution in the direction where the source stretches out (better than 0.1 arcsecond if seeing is smaller than 1 arcsecond).

Second, compared to galaxy-lenses, cluster-lenses strongly distort many background galaxies and form a lot of arclets in the same cluster. The efficiency of the lensing mainly depends on the projected mass density along the line of sight. So using the uniform projected distribution of background galaxies, one can derive the shape and the profile of the projected potential from the "distorsion map" outlined by the arclets (see Fig. 3), with a resolution of about 20 arcsec. This can be done either by using ray-tracing modeling (Grossmann and Narayan, 1989) or from purely analytical calculations with simple models such as a pseudo-isothermal sphere with possibly an elliptical term and a core radius. A statistical approach has been developed by our group (Mellier, Longaretti, in preparation) which uses the whole set of arclets to reconstruct the map of the dark matter in clusters without any assumption on the shape of the potential. All these modelings provide good constraints on the gravitational potential distribution and the total mass, but in order to derive a complete assessment of the matter content in clusters (visible matter, hot intracluster gas, and unseen mass) it is highly desirable to get X-ray maps for these cluster lenses. A proposal has been submitted in collaboration with the MPE (Max-Planck-Institut für Extraterrestrische Physik, collaborators H. Boehringer, M. Pierre and R. Schwarz), to survey the best cluster candidates with ROSAT.

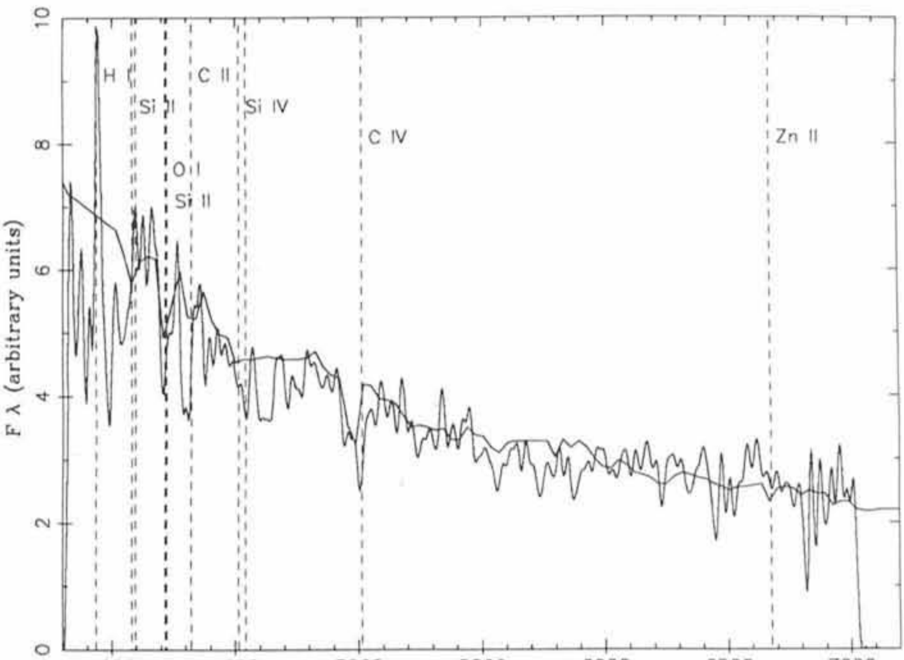


Figure 2: *Integrated spectrum of the arc in Cl2244-02 obtained at ESO with the B300 grism (exposure time 6 hours). The spectrum is flux calibrated in* F_λ (arbitrary units) and a synthetic spectrum of a non-evolved Im galaxy (Guiderdoni and Rocca-Volmerange, 1987) redshifted at z=2.237 is superimposed. Some of the best identified lines at this redshift are overplotted. One should especially note the emission line at 3938 Å identified with Lyα redshifted at z=2.237. This spectrum represents the most distant field galaxy presently known.

Giant Natural Telescopes to Probe High Redshift Galaxies

Since the sources of the arclets are lensed only because they happen to lie serendipitously behind a totally unrelated cluster, selection effects are kept to a minimum and the family of the arclets represents a large sample of a-priori very distant field galaxies.

For any given distribution in redshift of these galaxies, the number of arclets produced by a very rich cluster will depend strongly on the cluster redshift (or the distance lens-source). If most of the background galaxies lie closely behind the cluster the convergence of the lens will not be large enough to create large distorsions. Thus the multi-colour photometry and the number counts of arclets will be a new way to estimate the redshift distribution and the colour-evolution for these very faint objects (Ellis, 1990). Note however that the number of arclets can also change dramatically with the dynamical state of the distant clusters (Fort, 1990) and can be used as a critical test for the dynamical evolution of clusters.

For the luminous arcs in which a redshift was measured, it is difficult but possible to perform a large spectral survey from the UV to the near IR. The large tangential magnification increases the S/N ratio of the data either for spectroscopy or IR photometry, for a few objects which would be unobservable without this gravitational telescope effect. The IR data are crucial to characterize the oldest stellar population of the galaxy and they can constrain the epoch of formation of such a galaxy. That is why IR data are taken at UKIRT in collaboration with the Durham group, complementing our survey in the visible. It is likely that the study of arclets could reveal some distant and more primeval galaxies (Mellier et al., 1991).

Other Cosmological Consequences of the Arc Survey

Gravitational lensing is sensitive to the curvature of the universe. In principle one should obtain some constraints on the cosmological parameters from the study of lensing. For example, the distribution of several arcs in the same cluster is sensitive to q_o through the

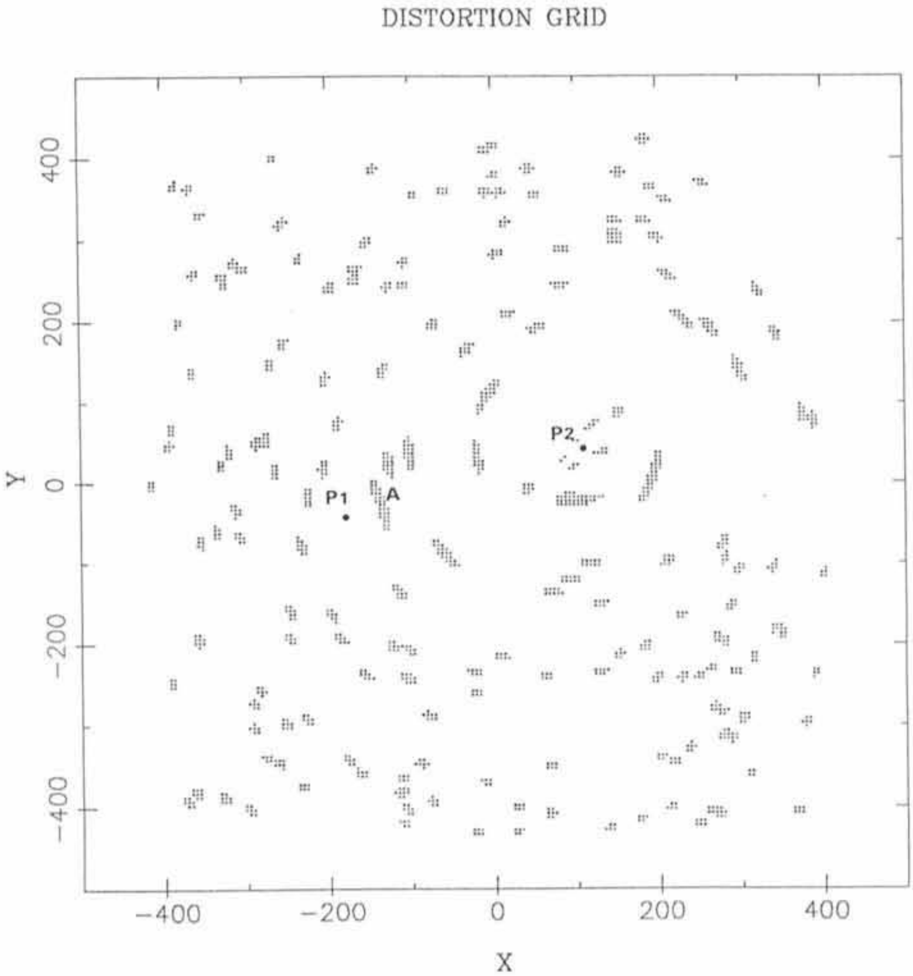


Figure 3: *Simulation of the gravitational distorsion of a population of galaxies randomly distributed at z=1.2. The cluster-lens is at redshift 0.23 with standard structural and dynamical parameters as expected for a rich cluster of galaxies. The cluster is composed of two potential wells located at P1 and P2. One should note the simulated "straight arc" located in A.*

ratio D_{ol}/D_{ls} where D_{ol} is the angular-diameter distance between the observer and the lens and D_{ls} is the distance lens-source. This ratio is independent of H_o and slowly varies with q_o. But a large number of arclets in the same cluster could possibly constrain the deceleration parameter. On the contrary, constraints on H_o are not evident. As was suggested by Kovner and Paczynski (1988), one should wait for a supernova occurring in the source, and measure the short time delay between the event in the two or three images in the arc. Another possibility was suggested recently (Soucail and Fort, 1991). A velocity gradient was detected along the giant arc in A2390 (Pello et al. 1991), and was interpreted as an intrinsic rotation of the source. Applying the Tully-Fisher relation on this galaxy, they deduced an absolute magnitude of the source and consequently determined H_o for a large distance modulus.

It is clear that this observational programme calls for large telescopes with sub-arcsecond seeing. It is extremely time-consuming, both for ultra-deep imaging in multi-band photometry (B, V, R, I, K) and for the spectroscopic follow-up of the most luminous arcs. The future European VLT will give new insight into the domain opened by this Key Programme. Observations with the VLT of the images produced by these Very Large Natural Telescopes are likely to open a completely new window to the early Universe.

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PROFILE OF A KEY PROGRAMME

High Resolution Studies of Quasar Absorption Lines

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The Key Programme described here intends to study the physics, chemistry and chemical composition of diffuse gas clouds between a redhift z ~ 0.6 to redshifts beyond z=4. With long integration times, it is now possible with CASPEC, and, for the first time, EMMI (1), to observe quasars fainter than 17.5 mag with a spectral resolution of 10 km s^{-1}, and signal-to-noise ratios as high as 50 from the UV to the near IR. High quality spectra of a selection of