However, at shorter distances from the star, we observe a very clear drop in the B filter, showing that the dust albedo seems to decrease by at least a factor of 4 when moving from 7.3 arcsec to 2.5 arcsec. This slow drop of the B albedo is also clearly seen in Figure 3.

This is an extremely interesting and totally new result, which seems to indicate that the nature of the grains is changing when moving inward. More precisely, a change in the grain size could not explain such a variation because larger grains should induce no colour changes while smaller ones should, on the contrary, favour the blue. However, a change in surface albedo of the grains could easily explain such a behaviour; from material albedoes by Gaffey and McCord (1979), a similar behaviour could be found in icy material more and more covered with dust.

If this explanation is correct, it seems to indicate that the grains in the β Pictoris disk are ices more and more dusty when going inward. This might be a first direct indication that a different situation prevails in the inner regions of the disk, namely at less than about 75 AU (5 arcsec), where planets are possibly forming.

We also have confirmed a slight asymmetry in the disk from one side to the other, but noticed an inversion of that asymmetry in the inner regions, leading to an average symmetric disk. This may again be the signature of planetary formation processes within the β Pictoris disk.

Conclusions

We have shown that a new observational approach does exist to look for very faint features near bright objects. Compared to classical stellar coronography, it allows observations closer to the star, particularly if quantitative results must be reached very close to it.

In the case of the β Pictoris disk, we confirmed previous results obtained at more than 6 arcsec from the star. Moreover, we were able to directly observe the disk down to 2 arcsec. The main results are:

- the disk extension continues down to 30 AU from the star, following an $r^{-3.6}$ power law;
- the disk colour is neutral in V, R and Ic at all observed distances;
- the disk colour drops down in the blue (B) when going inward, starting at about 75 AU from the star, to reach a factor of 4 reduction at 30 AU;
- a slight disk asymmetry (80%) is present, but is inverted within 100 AU from the star.

Obviously, this technique is very promising and a lot more is still to be done to further confirm these results and observe the disk even closer. From our first approach we are convinced that observing the β Pictoris disk down to less than one arcsec from the star is within the possibilities. Furthermore, this is potentially a very powerful technique to search for other protoplanetary disks around nearby stars, even if they are more inclined, as the β Pictoris one is still a unique phenomenon.

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Spectroscopy of Arcs and Arclets in Rich Clusters of Galaxies

G. SOUCAIL, Observatoire Midi-Pyrénées, Toulouse, France

1. Introduction

Since 1987, the redshift determination of the giant arcs observed in rich clusters of galaxies has been a great challenge for observers, as it was initially the only way to confirm the nature of the gravitational phenomenon. But the faint surface brightness of most of the arcs, only slightly compensated by the extension of the image, is partly responsible for the slow progress of such observations although their scientific impact is quite large.

Let us begin this paper with some chronological steps in the discovery and the observations of giant luminous arcs. The first main result, about one year after the discovery of giant arcs in two clusters of galaxies (Soucail et al. 1987, Lynds and Petrosian 1986), was the redshift measurement of the giant arc in Abell 370, a rich cluster at a redshift of 0.37. A strong emission line was detected all along the structure, with a curved slit punched with the PUMA system installed at the 3.6-m at La Silla. The line was immediately identified with the well-known [OII] line at 3727 Å, redshifted at 0.725. This important result was the confirmation of the hypothesis that we were observing a gravitationally distorted image of a background source through the cluster of galaxies. One year later we continued our study by showing that many clusters were acting as giant lenses on the numerous population of faint blue galaxies detected at the same period by Tyson (1988). For example in A370, many weakly distorted blue objects were detected, with an orthoradial orientation with respect to the cluster centre (Fort et al. 1988). These so-called "arclets" were also supposed to be images of distant background galaxies. But in this case, the confirmation of this idea is less obvious, because their magnitude is larger than 25, out of the capabilities of the present-day spectrographs. Many other clusters have now been observed by many people and a lot of them present similar structures. In particular, Tyson et al. (1990) have detected a strong excess of tangentially elongated objects in the very rich cluster A1689, mainly among the blue selected objects, by using very deep imaging in B and R.

The scientific interest in these examples of gravitational lensing is quite important, because it is a new tool for Observational Cosmology, and an approach of the mass distribution rather independent of other dynamical methods. The development of the new methods applied on lensed-clusters will be presented in a final report of the Key Programme 1-015-45K, "Arcs survey in distant clusters of galaxies", performed by the Toulouse group (Fort et al., 1990). The use of the "gravitational telescope" for probing the deep and distant Universe is also very promising and exciting and will be discussed here. A major goal of the spectroscopic observations is to derive the redshift of the largest and brightest arcs, and this for many reasons:

– It is the ultimate confirmation of the gravitational lensing hypothesis, especially in the cases for which other interpretations are possible (cluster galaxy seen edge-on, manifestations of galaxy-galaxy interactions, etc). In a few cases, such as the triple arc in C10024+1654, the identification of a change of parity in the different images (from high spatial resolution data) is also a clear evidence of the phenomenon (Kassiola et al., 1992).

– The redshift of one arc in a cluster fixes the geometrical scales of the lensing configuration and gives immediately the total mass within the critical radius. Consequently, the constraints obtained on the dark matter distribution are better (see for example the case of MS2137-23 in Mellier et al., 1992).

– The redshifts of two different arcs in one cluster could be very promising for constraining the value of q_0, provided one is able to reconstruct the gravitational potential of the cluster, and the two redshifts are distant enough from each other.

– Last but not least, the arc sources form a sample of very distant field galaxies at redshift larger than 0.6. It is very important to study their properties in the framework of galaxy evolution and formation, and their stellar content must be compared with evolutionary models (Guiderdoni and Rocca-Volmerange 1987, Bruzual and Charlot 1992).

Here I will present some preliminary results from the spectroscopic follow-up of the main arcs detected in our survey of rich clusters of galaxies (ESO Key Programme and CFHT Long-term Programme). The data have been collected on different telescopes with various instruments (3.6-m and NTT on La Silla, 3.6-m CFHT in Hawaii, 4.2-m WHT in La Palma), but they all correspond to faint objects and consequently low resolution spectroscopy with very long exposure times is required for each specific object.

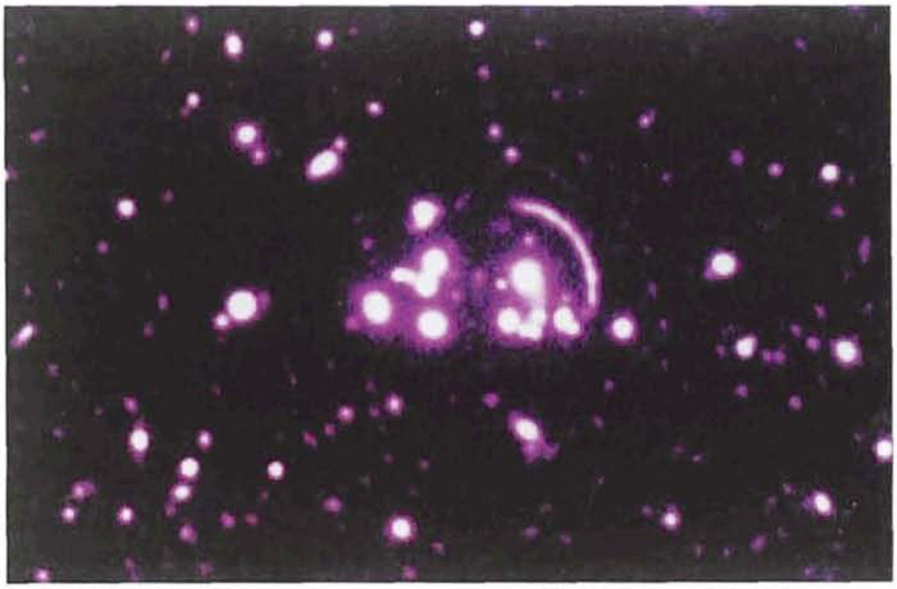

Figure 1: *Ultra-Deep B image of the cluster of galaxies Cl2244-02, from CFHT. One can see some substructures along the giant arc.*

2. Some Peculiar Cases of Redshift Determination

2.1 The Giant Arc in the Cluster Cl2244-02

The blue giant arc detected in the centre of Cl2244-02 (z = 0.329) is one of the most spectacular cases of gravitational lensing (see Fig. 1). Its very circular shape extends over more than 100° and its B-R colour index of 0.8 makes it one of the bluest arcs ever observed. More than 10 hours of integration were necessary at the 3.6-m with EFOSC in order to obtain a good signal on the continuum. An emission line was finally detected at a wavelength of 3940 Å and identified with Lyα redshifted at 2.238. This identification was also confirmed by the detection of several absorption lines (CIV 1549, SiII and SiIV) and the continuum observed in the rest-frame wavelength range of 1200–2000 Å is compatible with what is expected from starburst galaxies.

This rather secure identification makes the source of this arc one of the most distant field galaxies known up to now (Mellier et al., 1991). The stellar content seems "normal" with a star formation rate of a few tens of solar masses per year, a value far from the high numbers derived from the spectra of distant radio-galaxies!

2.2. The "Straight" Arc in Abell 2390

The spectroscopic data on this peculiar arc were collected at the 4.2-m William Herschel Telescope in La Palma. The surprising straight shape of the arc made the slit positioning easy! A total integration time of about 10 hours led to the detection of an emission line at 7130 Å and an underlying continuum, both compatible with a redshift of 0.913 (Pelló et al. 1991). We were also able to detect a velocity gradient along the arc with a line shift of 10 Å which we confirmed further with observations on EFOSC at a better resolution. This gradient is presently interpreted as an intrinsic velocity gradient inside the source, stretched by the gravitational distorsion of the cluster field. If so, it is the confirmation of the existence of a rotating disk with a maximum velocity of about 200 km/s (uncorrected for inclination). It has also been used tentatively to derive the Hubble constant H_0 through the Tully-Fisher relation (Soucail and Fort 1991).

Our first interpretation of the straight shape of the arc was the existence of a bi-modal deflecting potential with a source positioned in the saddle region between the two clumps of matter. Unfortunately we did not detect any over-dense region of galaxies on the external side of the arc, which was somehow problematic. Another possibility was

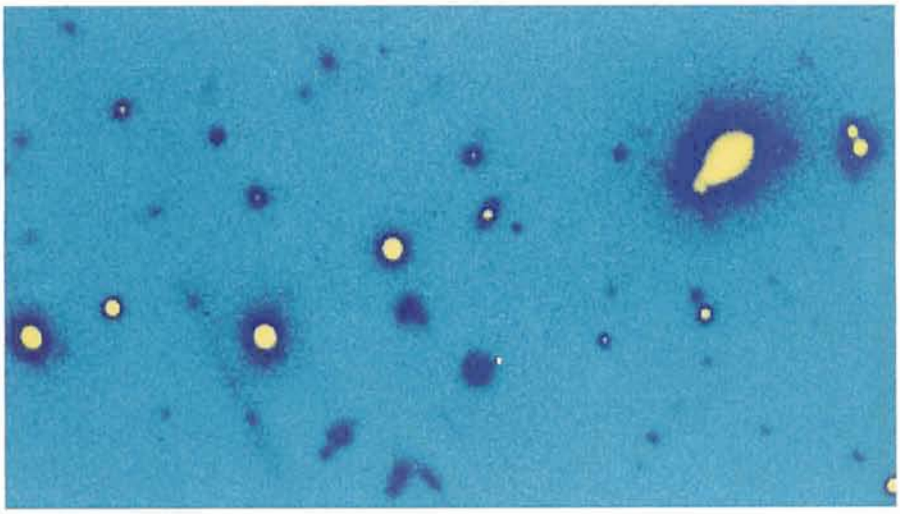

Figure 2: *High-resolution image of the centre of Abell 2390, from CFHT and with a I-band filter. The separation between the images of the two galaxies forming the arc is visible and also a slight change in the orientation of each image.*

suggested recently by Kassiola et al. (1992) that we see two interacting galaxies at $z = 0.913$. This hypothesis is reinforced by the infrared data (see below) because the arc presents a strong colour gradient in K (Smail et al. 1992) and also from high-resolution CCD frames collected at CFHT last year (Fig. 2). The separation between two smaller images is clearly evident in the I-band.

2.3. The Multiple Arc System in A2218

This cluster ($z = 0.175$) is one of the richest clusters of the Abell catalogue, with a giant cD in its centre. It shows many arclets in the central region, located around the cD and also around the second giant galaxy. A spectroscopic survey of the cluster has been performed at the 4.2-m WHT (La Palma) by Pelló et al. (1992). They collected spectra of several arclets, and got two source redshift measurements with a secure determination. The first one is located near the central cD and presents the spectrum of an E/Sa galaxy redshifted at $z = 0.702$. Its colours are redder than those of the cluster member, contrary to the other known arcs. The fact that the cluster redshift is only 0.17 also favours efficient magnification on rather low redshift sources. The second arclet is very blue and it lies around the second brightest galaxy. A strong emission line has been detected at 7580 Å with an underlying blue continuum, giving an identification of the [OII] λ 3727 line at $z = 1.034$. More data are being analysed on this cluster, mainly by multi-colour photometry used on the numerous populations of very faint arclets, in order to evaluate their "photometric redshift" distribution.

2.4 Some Results from Other Clusters

Many other arcs or arclets were observed spectroscopically over the last three years, sometimes with less success. In most cases, we did not succeed to get a redshift for the arc spectra without emission lines, as it is extremely difficult to detect absorption lines on a low S/N continuum. This means that it will be very difficult to measure redshifts between 1.1 and 2.3: [OII] λ 3727 is too far in the red ($\lambda > 7800$ Å) and Lyα is not redshifted enough ($\lambda < 4000$ Å). Between these two typical emission lines, no other emission lines are prominent in normal galaxies and we only expect to see absorption lines.

Presently two arcs fall in this category:

– The arclet A5 in the cluster A370 is the largest one of the weakly distorted images detected by Fort et al. (1989). Its B-magnitude reaches 22.7, but the surface brightness is only 25.5 mag. arcsec^{-2}. A spectrum was obtained with EFOSC, with the tentative detection of absorption lines giving a preliminary redshift of 1.305 (Mellier et al. 1991). The [OII] line was then predicted at a wavelength of 8590 Å. Our last data collected in December 1991 on EFOSC using a grism with a higher dispersion (R150, 3Å per pixel) are rather inconclusive: no emission line is visible at the expected wavelength, and the continuum level is only at 1 σ above zero. Anyway, even if the redshift of A5 is not confirmed, the photometric information available makes this object very peculiar and exciting. The colour indices (B-R) and (R-K) are very blue, the continuum in the optical range is flat and featureless. It is now quite unprobable that this corresponds to a cluster member at $z = 0.374$. Its very low flux in the near infrared (I and K bands) makes it rather "intriguing" and it should possibly correspond to a very distant and/or young galaxy, which needs to be re-observed.

– The giant arc in the cluster Cl0024+1654 ($z=0.39$) is the most interesting one to study in view of its large spatial extension and its splitting into 3 pieces. A curved slit was punched with PUMA (October 1989) in order to follow the three main parts of the arc, and despite a total integration time of 6 hours, a featureless spectrum was obtained, with no evident emission lines. A recent analysis of the image formation in this cluster by Kassiola et al. (1992) led them to predict the redshift of the arc source to be between 1.4 and 1.9 from theoretical arguments. Deeper data are expected in order to test their predictions.

Let us also present one counter-example of what was initially suspected to be an arclet. From deep imaging in the cluster of galaxies A483 ($z = 0.29$) we noticed several extended blue images around the cluster centre. In particular, two structures were detected, one going through the envelope of the cD, and the other one extended over 9″ located a bit more than 1′ north of the cD. In December 1991, we got 4 hours exposure in spectroscopy on the second of these objects. After data reduction we found a redshift of 0.274! This object is most probably an edge-on spiral galaxy belonging to the cluster and not an arclet. One must conclude that people have to be very careful when they announce the discovery of arcs or arclet candidates. Only detailed multi-colour photometry and/or spectroscopic data can give some confidence in the gravitational arcs hypothesis, if one cannot detect a clear multiple arc system with a counter-image or possibly a parity change between the images.

3. Gravitational Lensing and Distant Galaxies

The sources of the gravitational arcs and arclets are potentially a very useful sample of very distant galaxies, from which we begin to gather extensive spectrophotometric data. At least ten of them are presently spectroscopically confirmed and the spectra generally include information on the continuum or the large-scale spectral energy distribution (Table 1).

We must also consider the possible selection biases introduced in the sample before any analysis and comparisons with other surveys. The arcs and arclets are generally detected by their blue colour (B-R < 1) with respect to the

Table 1. *Summary of the spectrophotometric survey of arcs and arclets.*

Cluster	z_{cl}	z_s	B	R	B-R	R-K	μB	γ	B_{int}	R_{int}
A370 (A0)[1]	0.374	0.725	21.1	19.4	1.7	4.1	24.6	12	23.8	22.1
A370 (A5)[2]	0.374	1.305?	22.7	22.3	0.4	~3.0	25.4	6	24.7	24.2
Cl2244-02[2]	0.336	2.237	21.2	20.4	0.8	3.0	25.3	20	24.5	23.7
A2390[3]	0.231	0.913	21.9	20.0	1.9	4.2	25.3	12	24.6	22.7
A2218 (# 359)[4]	0.176	0.702	24.3	21.4*	2.9	—	25.0	4	25.8	22.9
A2218 (# 289)[4]	0.176	1.034	22.5	21.7*	0.8	—	24.2	5	24.2	23.4
A963 N[5]	0.206	0.771	23.6	23.1	0.5	3.5	25.5	4	25.1	24.6
Cl0024+1654[2]	0.391	?	23.0	22.3	0.7	3.3	25	4	24.5	23.8
S506 (Cl0500-24)[6]	0.321	0.91?	21.0	19.8	1.2	<3.0	—	8	23.2	22.0
A2163 (A1)[7]	0.203	0.742	24.2	21.8	2.4	—	—	3	25.4	23.0
A2163 (A2)[7]	0.203	0.728	23.1	21.2	1.9	—	—	3	24.3	22.4

*Gunn r filter; [1]Soucail et al., 1987; [2]Mellier et al., 1991; [3]Pelló et al., 1991; [4]Pelló et al., 1992; [5] Ellis et al., 1991; [6]Giraud 1992, preprint; [7]Soucail G., Amaud M., Lachièze-Rey M., Mathez G., in preparation.

redder cluster members but this is not always the case (see for example the "red arc" in A2218, Pelló et al. 1992). More important is the fact that the sample is limited in surface brightness more than in magnitude; this is due to the fact that to detect the continuum of the spectra of these objects in a reasonable exposure time implies that the surface brightness does not exceed $\mu_B = 25.5$. Remember that in gravitational lensing, surface brightness is conserved and that magnification means extension of the image of the source. Finally the sample is only based on galaxies with redshift larger than 0.7 because it roughly corresponds to the minimum redshift above which lensing is efficient, for a typical deflector at a redshift of 0.2 to 0.4 ($z_{Source} > 2z_{Cluster}$).

But the sources of the arcs belong to the family of FIELD galaxies (which are not detected by their radio emission for example), and their intrinsic magnitudes, corrected from the gravitational magnification, are in the range [24; 25] in B. This range is at least one magnitude fainter than the magnitude range of the deepest spectroscopic surveys of field galaxies performed by Cowie et al. (1991) for example. So it is interesting to explore the redshift distribution which is centred around 1 in our sample. One should note for example that with the exception of the peculiar case of Cl2244-02, about 70% of the galaxies have a redshift smaller than 1, and the median redshift is 0.9. Moreover, in view of their spectra, these objects are not observed in a phase of violent star formation although emission lines typical of HII regions are present in most of them. Moreover, when we have high-resolution images of the giant arcs, we often see sub-structures inside the arcs. This still preliminary result could suggest either that we see merging clumps at large z or that inside the distant galaxies disks or spiral arms are already formed.

4. Infrared Photometry of Large Arcs

In order to increase the observed spectral range of the galaxies, a photometric survey of the arcs has been performed by our colleagues from Durham (UK) in the K band (Smail et al., 1992). The main advantage of the K band at 2.2 μm is that it scans a portion of the spectrum dominated by the old stellar population, and is more indicative of the history of star formation than blue photometry, very sensitive to recent star formation. Anyway, the combination of both magnitudes as well as the redshift indication give a good tool to study the distant galaxies and their entire spectral content. Then it is shown that although most of the arcs have blue colour indices, none of them remain undetected in K. But for those at $z > 1$, the old population does not contribute significantly to the K flux, so the sample is not consistent either with a non-evolutionary model of galaxy or a model with a single initial burst of star formation. This probably means that the history of star formation in these galaxies is rather continuous, up to a redshift of about 1.

5. Conclusions

I have presented in this article the status of the survey in 1992, and I should emphasize the fact that the increase of the sample of arcs with a secure redshift measurement is very slow, due to the difficulties of the observations and the long exposure times involved for these faint objects. But the detection of new arcs and arclet candidates still goes on, especially in the framework of the ESO Key Programme "Arcs and arclets survey" and the similar one at CFHT. We expect some new, very exciting data over the next year. In particular, we are very excited by the new arc system discovered in the cluster MS2137-23 (Fort et al. 1992, Figure 3): a long tangential arc has been detected as well as the first case of a radial arc candidate. This peculiar lensing configuration has been expected for a long time, but as radial images are supposed to form near the cluster centre, in most cases they fall in the envelope of the giant central galaxies. In the case of MS2137-23, the radial arc candidate was detected by its blue colour, and a modelling of the gravitational potential of the cluster was proposed by Mellier et al. (1992) which takes into account a large number of observational parameters. The spectroscopic confirmation of the radial image would fix one

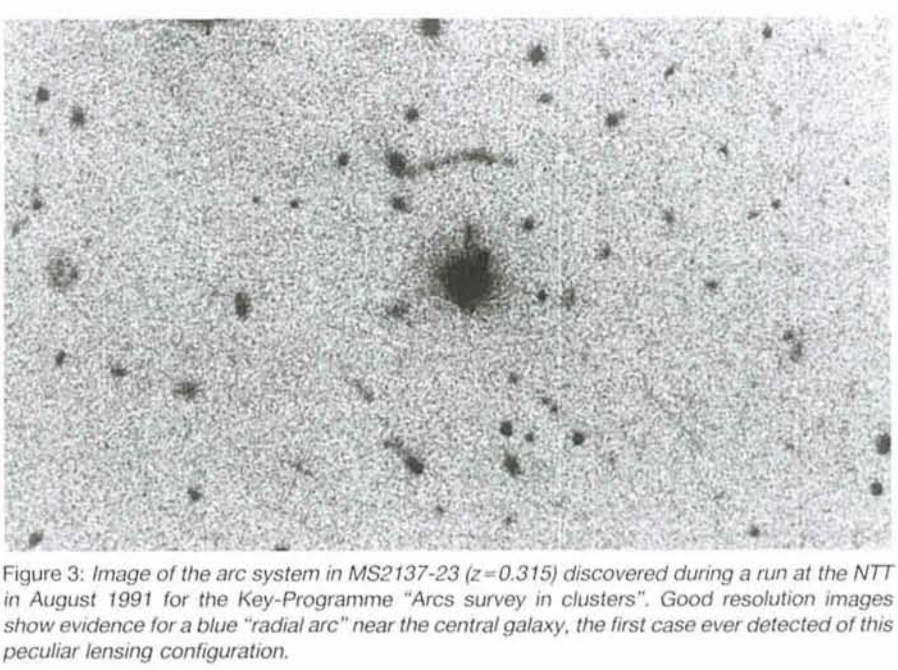

Figure 3: *Image of the arc system in MS2137-23 (z = 0.315) discovered during a run at the NTT in August 1991 for the Key-Programme "Arcs survey in clusters". Good resolution images show evidence for a blue "radial arc" near the central galaxy, the first case ever detected of this peculiar lensing configuration.*

of the still unknown parameters, increasing the number of constraints of the model.

For the arclets or the weakly magnified galaxies which are too faint to be observed spectroscopically, we also expect some progress by using multi-colour photometric data spread over a large spectral range, such as B, R and I colours. In that case we can compare the colour indices of the objects with the predictions of spectrophotometric models of galaxy evolution, in order to evaluate a "photometric redshift". This method is being calibrated with the known arcs, and we are conscious that it is only useful in a statistical way, when a large number of arclets is being observed. The preliminary results of the method, applied in the field of A370 show that most of the galaxies have colours compatible with galaxies at redshift around 1, reinforcing the results presented above (Fort et al., in preparation).

Last but not least, in a few optimal cases, we expect to get a complete set of data in some clusters: high-resolution X-ray map with ROSAT, multiple arcs and a lot of arclets and weakly distorted images of background galaxies for a reconstruction of the 2D gravitational potential of the Dark Matter from the centre to the external radius of the cluster. The redshift of the giant arcs is in this case fundamental in order to fix the scaling of the potential in the lens modellings.

The use of the gravitational telescope for the study of distant galaxies appears to be a powerful and original tool, which is probably not yet fully used. For example, we can also expect to find some "exotic" magnified objects, such as very distant quasars (La Borgne et al., 1990) or we hope to "see" some spatial structures in galaxies at z = 1 through the distortion of the clusters. The arc survey opened for us a new window in the z = 1 Universe!

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Quasar Absorption Spectra: The Physical State of the Intergalactic Medium at High Redshifts

E. GIALLONGO, Osservatorio Astronomico di Roma, Monteporzio, Italy

S. CRISTIANI, Dipartimento di Astronomia, Università di Padova, Italy

A. FONTANA, Dipartimento di Fisica, II Università di Roma, Italy

D. TRÈVESE, Istituto Astronomico, Università di Roma "La Sapienza", Italy

1. Introduction

An important source of information on the distribution and the physical state of the intergalactic medium (IGM) up to redshift $z \simeq 5$ is provided by the study of the absorption spectra of high redshift quasars. The crowd of narrow absorption lines seen shortward of the QSO Lyman-α emission is thought to be due mainly to Lyman-α absorptions caused by intervening clouds along the line-of-sight (Lynds 1971; Sargent et al. 1980).

Direct measures of column densities and doppler widths of the absorption lines provide typical values of $N_{HI} = 10^{14}$ atoms cm^{-2} and $b = \sqrt{2}\sigma$ = 20–30 km s^{-1} (Carswell et al. 1987, 1991) correspondent to $T_c \sim 2-5 \times 10^4$ K, assuming thermal broadening. However, Pettini et al. (1990) claim typical b values as low as b = 17 km s^{-1} and a tight correlation between b and N_{HI} parameters which suggests lower temperatures and would imply a further important constraint on the physics of the clouds. More data are necessary to resolve this controversy.

The most recent and accurate estimate of the cloud sizes has been obtained by Smette et al. (1991) from the spectra of a gravitationally lensed high-redshift quasar UM673 (z_{em} = 2.7). They derive lower and upper limits of 12 h_{50}^{-1} kpc and 160 h_{50}^{-1} kpc respectively, for the diameter of spherical clouds, or 24 kpc and 320 kpc, for oblate spheroids with an axis ratio < 0.1.

Under these conditions, gravitational energy is overwhelmed by thermal energy and the clouds could be confined by a hotter, highly ionized and diffuse IGM if non-baryonic dark matter does not