THE ASTROPHYSICAL JOURNAL, 380:334–343, 1991 October 20

SPECTROSCOPY OF THE GRAVITATIONAL ARCS IN Cl 2244−02, A370 (ARCLET A5), AND Cl 0024+1654[1]

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Received 1991 January 18; accepted 1991 April 29

ABSTRACT

We analyze new spectroscopic data on the blue giant arc in Cl 2244−02, on the arclet A5 in Abell 370, and on the split arc in Cl 0024+1654. A probable redshift $z = 2.237$ is derived for the source of the Cl 2244−02 arc, making this object one of the most distant "field" galaxies known today. A star formation rate is estimated from the Lyα intensity and compared to other distant field galaxies. For A5, no prominent emission line is found, but three absorption lines point to a tentative redshift $z = 1.306$. The spectra of the four parts of the Cl 0024+1654 arc look rather similar, but the absence of any spectral feature allows only the determination of a redshift range: $1 < z < 2.1$.

The systematic search for such arcs and/or arclets, and the Toulouse spectroscopic survey of arcs which follows up, seems one of the promising methods of obtaining spectra of extremely distant field galaxies and of constraining their early evolution.

Subject headings: galaxies: clustering — galaxies: redshifts — gravitational lenses

1. INTRODUCTION

The spectroscopy of arcs was first performed to confirm the hypothesis of the gravitational effect of rich clusters on the images of well-aligned background galaxies. The definitive evidence that the redshift of the giant arc in Abell 370 is about twice the cluster redshift (Soucail et al. 1988; Lynds & Petrosian 1989) was the starting point of similar attempts on many other arcs in various clusters. In particular, several teams tried to get the redshift of the arc in Cl 2244−02, first observed by Lynds and Petrosian, in spite of its very low surface brightness, only a few percent of the night sky. Soucail et al. (1987) found in the wavelength range (4500–7200 Å) a flat spectrum with a low signal-to-noise ratio precluding a redshift determination. Miller & Goodrich (1988) published a featureless spectrum of the arc in the spectral range (4400–7200 Å). Lynds & Petrosian (1989) seemed to detect an emission line at 6381 Å, quite doubtful due to a residual from sky subtraction, while a possible interpretation of these data with a redshift $z = 0.83$ was announced by Bergmann, Petrosian, & Lynds (1990). Hereafter, we will show that the spectroscopy of arcs is still an extremely adventurous observing challenge, even with the largest telescopes presently available. In particular, better spectroscopic data over a larger spectral range, especially in the blue (3800–7200 Å), where some spectral identifications are now possible, lead more likely to a redshift $z = 2.237$ for the Cl 2244−02 arc.

So far, only a few of the known arcs have convincing redshifts, and this number needs to be increased. This input is important for the modeling of the lensing configuration used to derive the amount of dark matter within the cluster (the redshift of the source is the parameter which fixes the angular scale).

But another challenge for arc spectroscopy is a better understanding of the history of formation and evolution of normal galaxies. To our knowledge, three systematic searches have been undertaken so far for standard galaxies with comparable redshifts. All three have been performed in fields around quasars with metal absorption lines and/or large hydrogen column densities. Hunstead, Pettini, & Fletcher (1990) have performed long-slit, 1.5 Å resolution, spectroscopy of quasars with damped Lyα absorption lines. They detected a narrow emission line at the 4 σ level, attributed it to Lyα in a gas-rich galaxy at $z = 2.465$, and derived the corresponding star formation rate (SFR). Deharveng, Buat, & Bowyer (1990) derive upper limits to the SFR in high-redshift galaxies from an unsuccessful attempt to find galaxies from narrow band imagery in such fields. Finally, the ESO key program conducted by Bergeron, Christiani, Pierre, and Shaver consists of systematic deep imaging, followed up by spectroscopy of galaxy candidates. In these cases the light of the background quasar provides the possibility of getting spectral information on the gaseous content of these intervening galaxies.

Thanks to the gravitational magnification of background galaxy images by clusters, arc-like objects form a new class, less affected by observational selection biases, of high-redshift "normal" galaxies (as opposed to bright distant objects such as quasars, AGNs, strong radiogalaxies, or BCMs). The determination of the spectral energy distribution is not out of reach of present-day techniques for some of them, allowing a precise idea about the stellar population.

The larger the magnification, the easier will be the observation if the surface brightness is not too low. About only 10 large arcs have been detected to date. Fortunately, a large number of the so-called arclets were observed in the field of several rich clusters such as A370 (Fort et al. 1988; Tyson, Valdes, & Wenk 1990). These elongated objects have smaller tangential magnification, but are far more numerous. They can be studied by multiband photometry (U, B, V, R, I, K) and the brightest ones by spectroscopy.

Such observations are also important in view of the apparent discrepancy between the ultradeep CCD photometric surveys (Tyson 1988; Metcalfe, Shanks, & Fong 1988; Cowie et al. 1988) and the deep spectroscopic surveys (Colless, Ellis, & Taylor 1989; Colless et al. 1990; Koo & Kron 1988).

[1] Based on observations collected at the European Southern Observatory at La Silla, Chile, and at the Canada-France-Hawaii Telescope at Mauna Kea, Hawaii.

The former characterized by limiting magnitudes of the order of 29 mag arcsec^{-2} in B, tend to find a large population of faint and blue "flat-spectrum" objects which could be, at least for a substantial part of them, at $z > 1$ and undergoing strong star formation. On the contrary, the results from redshift surveys (up to magnitudes $b_J = 22.5$) show that the mean redshift of complete samples of such objects is around 0.3 and more compatible with non-evolutionary models (Ellis 1990).

In § 2 a preliminary analysis of the spectral content of the arc in Cl 2244−02 is presented, which corresponds to one of the most distant normal field galaxies currently known. Its spectrum is also compared with those of high-luminosity galaxies associated with steep-spectrum radio sources (Chambers, Miley, & Joyce 1988; Chambers, Miley, & van Breugel 1990; Lilly 1989). In § 3 the tentative redshift determination of one of the "arclets" detected in Abell 370 and named "A5" by Fort et al. (1988) is also presented. From our data, its most probable redshift is $z = 1.306$ leading to a second arclike feature with a known redshift in the same cluster. The implications for lens modeling will be discussed. In addition, preliminary data on the split arc in Cl 0024+1654 are displayed even if no redshift determination is achieved. In § 4 we present the impact of all the redshift measurements of arcs (including these data), compared to more standard studies of distant galaxies.

2. THE GIANT ARC IN Cl 2244−02

2.1. *Observations and Data Reduction*

The preliminary photometry of the cluster center was published by Hammer et al. (1989). The integrated magnitude and color index of the arc are key parameters for our study of distant galaxies, and we remeasured them, paying special attention to the contamination by the envelope of the galaxy near the arc. From the B-frame we find the value $B = 21.4 \pm 0.1$ for the entire arc, in good agreement with other published values: $B = 21.51 \pm 0.1$ in Hammer et al. (1989) and $B \simeq 21.0$ in Lynds & Petrosian (1989). However this is not the case in R, where the contamination by the nearby galaxy is larger. Instead of an integration inside boxes, followed by subtraction of the galaxy contribution estimated in a symmetric box, we directly integrated the arc contribution above the galaxy envelope by drawing profiles along the x-direction for various y-values. We derive a color index: $B-R = 0.77 \pm 0.15$, only marginally consistent with the previous value given by Hammer et al. ($B-R = 1.11 \pm 0.03$) and hardly compatible with that in Lynds & Petrosian ($B-R \simeq 1.6$), who probably neglected the contamination by the galaxy, which is critical in the R band. The overall photometric results are summarized in Table 1.

The spectroscopic data come from three different runs (Table 2). The first one occurred during the nights 1987 August 19–22 at CFHT. The telescope was mounted with the focal reducer ($F/8$–$F/2$) and the multiaperture system PUMA1 (Fort et al. 1986). In order to improve the S/N ratio of the spectrum of the arc, a special aperture mask was punched, with a curved slit matched to the shape of the arc and another one for sky reference, both with approximatively 2″ width. Five exposures of 5400 s each were obtained in good weather conditions, with a dispersion of 8 Å pixel^{-1} and a spectral range covering 4500 to 7200 Å. The other spectral data were obtained with the 3.6 m telescope and EFOSC at ESO, during two runs in 1987 October 18–21 and 1988 October 6–10. Two sets of grisms were used with different apertures. First, the UV300 grism (dispersion of 6 Å pixel^{-1}, spectral range 3600–6500 Å) was mounted with a curved slit punched with PUMA2, and three frames of 5400 s each were obtained. We also used the B300 grism (dispersion of 6.5 Å pixel^{-1}, spectral range 3800–7200 Å) both with a curved slit and with a long slit of 2″ aperture. In this last configuration we lost some of the flux, but this was partly compensated by a better sky subtraction (the most crucial point for very faint objects). Four frames were co-added, with a total integration time of 20,000 s. Such a large amount of data was necessary to obtain a significant S/N ratio, as the mean surface brightness of the arc is about 5% of the sky brightness ($\mu_B = 25.2$ mag arcsec^{-2}). In the spectrum obtained with the B300 grism, the S/N ratio is about 12 in V and 9 in B, whereas it is only 6 in V and 4 in B with the UV300 spectrum.

The data reduction was performed using standard procedures, except some modifications introduced for the curved slits. Each column was wavelength-calibrated independently, since the position of the null-deviation wavelength on the CCD varies from column to column. Then they were added to get one single line for the spectrum (sky + object) and one for the sky. After sky subtraction, the spectra were flux-calibrated and then co-added, mostly to increase the S/N ratio of the continuum. For the identification of spectral features, we preferred to work on the uncalibrated spectra because this last operation amplifies residual defects and the noise in the blue part of the spectrum, where the transmission of the optics decreases. Finally, a slight smoothing was applied to reduce the shot noise.

TABLE 1

PHOTOMETRIC DATA OF THE GIANT ARC IN Cl 2244−02

Parameter	Cl 2244−02	A5
Integrated magnitude B	21.4 ± 0.10	22.3 ± 0.15
Surface brightness μ_B	25.2 ± 0.20	25.4 ± 0.20
$(U-B)_{\rm photom}$	-0.66 ± 0.15	...
$(B-R)_{\rm photom}$	0.77 ± 0.15	1.05 ± 0.15
$(B-V)_{\rm spectro}$	0.20 ± 0.15	0.44 ± 0.15
$(V-R)_{\rm spectro}$ [a]	0.53 ± 0.15	0.42 ± 0.15
$(B-R)_{\rm spectro}$ [a]	0.73 ± 0.15	0.86 ± 0.15

[a] Not corrected for atmospheric refraction.

TABLE 2

SUMMARY OF OBSERVING RUNS

Date; Site	CCD Read-out Noise	Standard Stars
1987 Aug CFHT	RCA2 bin $\sigma = 60e^-$	BD 25 39 41 Feige 15
1987 Oct ESO	RCA2 number 11 bin $\sigma = 57e^-$	Hiltner 600
1988 Oct ESO	RCA2 number 11 bin $\sigma = 57e^-$	Feige 110
1989 Oct ESO	RCA2 number 8 bin $\sigma = 22e^-$	Feige 110

2.2. *Spectral Analysis*

Photometric and spectroscopic data both show a flat continuum which confirms our previous results (Soucail et al. 1987). However the spectrum presents a significant increase of the flux below 5000 Å (see Fig. 1). Its overall shape is indeed quite similar to those of some UV spectra of starburst galaxies of

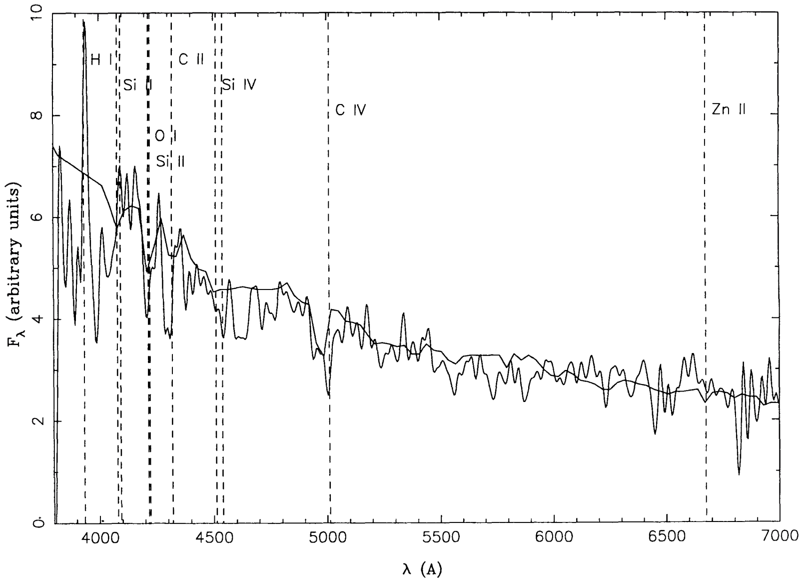

FIG. 1.—Integrated spectrum of the arc in Cl 2244−02 obtained at ESO with the B300 grism (*see text*). Spectrum is flux-calibrated in F_λ (arbitrary units), and a synthetic spectrum of a nonevolved Im galaxy (Guiderdoni & Rocca-Volmerange 1987) redshifted at $z = 2.237$ is superposed. Some of the best identified lines are overplotted.

H II regions in the range 1200–2000 Å (Rosa, Joubert, & Benvenuti: 1984). This suggests that the object is highly redshifted, probably at a redshift larger than 2. The color index $U-B = -0.66 \pm 0.15$ proposed by Wlérick et al. (1990) from their observations with the electronographic camera reinforces this idea. It corresponds to an increase by a factor of 1.2 in flux between 3800 and 4400 Å.

The three resulting spectra obtained with the three grisms are shown in Figure 2. They have been superposed in order to cross-correlate possible features, each one being not very far above the noise level in the individual spectra. The most obvious feature found in these data is an emission line centered at $\lambda = 3940 \pm 2$ Å which is detected on the two blue spectra: on the UV300 spectrum, it is detected at 5.8 σ above the continuum and its FWHM is 17 ± 3 Å, and on the B300 spectrum the maximum is at 3.8 σ above the continuum with a FWHM of 22 ± 3 Å. Its equivalent width, averaged over the different sets of data is $W_\lambda = 40 \pm 5$ Å. This line has also been detected independently by other observers at Palomar (Lawrence & Turner 1989, private communication). Lynds & Petrosian (1989) claimed to have detected a "relatively strong emission line" in their spectrum of the Cl 2244−02 arc at $\lambda = 6831$ Å, which they later identified as [O II] λ3727 redshifted at $z = 0.83$ (Bergmann et al. 1990). This line is actually undetected on our data and probably results from sky subtraction residual associated with the strong OH bands of the sky spectrum.

All the other features identified on the spectra are absorption lines. Because of the small S/N ratio of the individual

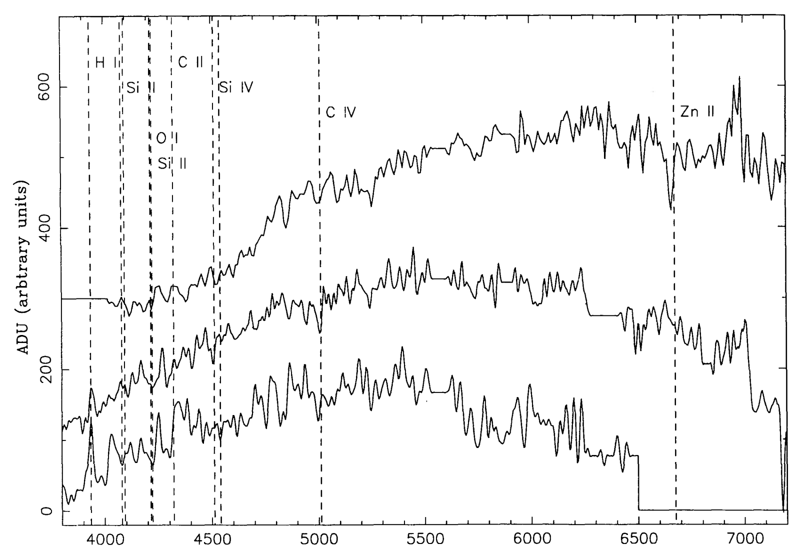

FIG. 2.—Three independent spectra of the arc in Cl 2244−02 obtained with three different grisms. From bottom to top: (1) Taken with the UV300 grism at ESO; (2) with the B300 at ESO; and (3) comes from CFHT. Those spectral features which are reproducible from one spectrum to another are noted.

TABLE 3

MAIN LINES DETECTED IN THE SPECTRUM OF THE ARC IN Cl 2244−02

Line	λ_0	λ (observed)	z	Equivalent Width (Å)
Lyα	1215.7	3938	2.239	40 ± 5
O I, Si II	1302.2, 1304.4	4219	2.239	10 (?)
C II	1334.5	4293	2.238	8 (?)
Si IV	1393.8, 1402.8	4520	2.236	...
		4850	...	8
C IV	1548.2, 1550.7	5000	2.228	6
		5245	...	3
		5731	...	4
Zn II	2062.0	6670	2.235	...

spectra we chose to consider features detected on at least two different spectra as true absorption lines. These lines are listed in Table 3, with an evaluation of their equivalent width, but this value is questionable for the faintest lines.

2.3. *Identification with a Redshift z = 2.237*

Several identifications were attempted with the list of detected lines, but only a few possibilities were allowed for the identification of the emission line. It is almost certainly not [O II] λ3727, which should give a redshift of 0.057, since no other line is consistent with this redshift. Such a low redshift should also exclude the lensing hypothesis for this arc and would mean that we discovered a new class of nearby astronomical objects! Actually, lensing is the most reasonable explanation because of the similar properties between this arc and other ones with already published redshifts.

Searching among the strongest emission lines known in the UV (such as C IV λ1549, C III] λ1909, or Lyα) leads to several possible redshifts: 1.064, 1.544, and 2.239. For each of these redshifts, all the other absorption lines were tentatively recognized using the list given in Morton, York, & Jenkins (1988). Finally a single redshift, for which the emission line is Lyα, allows the identification of more than half the detected absorption lines. Note that in this case the other lines such as C IV are found in absorption within one pixel accuracy. Table 3 summarizes the identifications for this redshift. From the six well-identified lines in this table, the mean redshift found is: $\langle z \rangle = 2.236 \pm 0.004$, but there is a residual shift of 1.5 pixels for the C IV line. Such a discrepancy cannot be understood in terms of a velocity field, but it may result from an additive glitch in the residual noise pattern. Unfortunately, the quality of the individual spectra does not allow us to check whether or not this shift is systematic.

If we exclude this line eventually spoiled by noise, the mean redshift is: $\langle z \rangle = 2.237 \pm 0.0016$, which is the value we will consider in this paper.

Even with this optimal identification, at least three lines remain unidentified with typical strong features known in UV spectra (see Table 3). They could correspond either to undetermined lines at $z = 2.237$, or to other lines at another redshift corresponding to intervening matter on the line of sight. For instance the 5730 Å line could correspond to the G band of elliptical galaxies, at the redshift of the cluster ($z = 0.33$). In that case, these absorption lines could be due to the small light contamination by the envelope of the bright galaxy near the arc ($z = 0.335$).

2.4. *Some Properties of a Field Galaxy at z = 2.237*

Using the photometry of the arc, we can evaluate its integrated magnitude, especially from the B-photometry where the contamination by the nearby galaxy is smaller: $B = 21.4 \pm 0.1$. The source is hardly resolved in width (1″), and the length of the arc is 19″. The total magnification factor, that is, the ratio between the surface of the arc and the surface of the source without magnification, is about 20 ± 10 assuming a typical radius of 10 h_{50}^{-1} kpc for the galaxy with $h_{50} = H_0/50$ km s^{-1} Mpc^{-1}. So this galaxy would have a magnitude $B = 24.7 \pm 0.5$ in the absence of gravitational magnification, and it should be totally unobservable spectroscopically. Note that as the surface brightness is conserved in gravitational lensing, the value of $\mu_B \simeq 25.2$ is still valid for the source. Corrected from the heterochromatic dimming factor $(1 + z)^3$ at $z = 2.237$ the mean surface brightness of the source becomes $\mu_B \simeq 21.4$ without any k-correction. This value, although rather bright for a normal galaxy, is difficult to compare with nearby galaxies for many reasons: the wavelength range is not the same, and no evolution correction has been added. We can include some k- and e-corrections taken from evolutionary models such as the ones in Rocca-Volmerange & Guiderdoni (1988). With $H_0 = 50$ km s^{-1} Mpc^{-1}, and for a Sd-type galaxy they give $k = +0.60$ and $e = -0.88$ if $q_0 = 0.5$, and $k = +0.35$ and $e = -0.73$ if $q_0 = 0$. In any case, the total correction does not exceed -0.3 to -0.4 mag, and the corrected surface brightness remains smaller than $\mu_B = 22$ but no more than 1 mag brighter than nearby field galaxies. The absolute magnitude of the source is $M_B = -21.2 \pm 0.5$ if $q_0 = 0.5$, and $M_B = -22.2 \pm 0.5$ if $q_0 = 0$. These magnitudes seem rather bright for normal field galaxies at $z = 0$, but not ultrabright. For comparison, the most distant known galaxy, 4C 41.17, which is a radio galaxy at a redshift of 3.8, has an R-magnitude of 22 and a Lyα flux of 5.8×10^{44} ergs s^{-1}, corresponding to an equivalent width larger than 1000 Å (Chambers et al. 1990). The galaxy we are studying has an equivalent width in Lyα of 40 Å on the spectrum or 12 Å in the rest frame and is consequently at least 6 times fainter in the continuum and 25 times fainter in the Lyα line! Compared to other known very distant galaxies which are all radio-emitting ones, this value is very small (Spinrad 1988). But for radio galaxies, it is not easy to separate the nuclear and stellar contributions in the Lyα flux, whereas the fact that C IV λ1549 is detected in absorption and that C III] λ1909 is not detected indicates that the emitted light is dominated by stars rather than by any type of active nucleus. The continuum flux in the rest frame far-UV is also indicative of the presence of a large fraction of very young stars.

2.5. *Estimation of the SFR*

We can try to estimate the SFR in the galaxy under some assumptions discussed now. We will follow the results presented by Donas et al. (1990) who calibrate the SFR in nearby galaxies from their UV flux measured at 2000 Å, arguing that the light emitted at these wavelengths is characteristic of stars of intermediate mass (2–5 $M_\odot$) whose lifetime is smaller than 3×10^8 yr. In our case, this corresponds to $\lambda \simeq 6470$ Å in the observed spectrum, and the flux can be estimated from the R-magnitude, corrected for the gravitational magnification and for the cosmological factor $(1 + z)$ corresponding to the increase in wavelength intervals.

The apparent R-magnitude of the source would be 23.93 without magnification, corresponding to a received flux in this band of the order of 4.9×10^{-19} ergs s^{-1} cm^{-2} Å^{-1}. Accounting for the cosmological correction, this corresponds to a UV flux of about 1.6×10^{-18} ergs s^{-1} cm^{-2} Å^{-1}. Then the absolute flux will strongly depend on q_0: with $q_0 = 0.5$, the absolute UV flux at 2000 Å is approximately 5.3×10^{40} h_{50}^{-2} ergs s^{-1} Å^{-1} from which we derive a SFR of 7 h_{50}^{-2} $M_\odot$ yr^{-1}. This value is increased up to 19 h_{50}^{-2} $M_\odot$ yr^{-1} for an open universe. In any case this evaluation is poorly constrained although the magnification factor can be reasonably estimated: the dust content of the galaxy is completely unknown at this redshift! Another method based on the Lyα flux emitted by the galaxy, translated in terms of the SFR using the empirical relation developed in Kennicutt (1983) was tentatively used, but it implies the knowledge of the Lyα/Hα ratio, which in turn is strongly dependent on the dust content of the galaxy. Without any correction we found a SFR lowered by a factor of 4 compared to the one from the UV flux, which is probably due to a bad conversion between Lyα photons and Hα ones. In any case, these values are rather low and cannot be compared to the ones found in 3CR radio galaxies where the standard value of the SFR is 100–500 $M_\odot$ yr^{-1}. On the contrary the arc in Cl 2244−02 is probably more similar to the absorber of Q0836+113 (Hunstead et al. 1990). In this object, Lyα emission was detected in the damped line observed in the QSO spectrum indicative of some star formation in a disk galaxy at $z = 2.465$. Their inferred SFR is around 1 h_{50}^{-2} $M_\odot$ yr^{-1} (for $q_0 = 0.5$), but the stellar continuum of the galaxy was not detected. Deharveng et al. (1990) have carried out some narrow band imaging in order to detect Lyα emission from some high-redshift absorbers seen in the spectra of QSOs. Their nondetection puts some limits on the SFR ranging from 20–60 h_{50}^{-2} $M_\odot$ yr^{-1} according to the adopted q_0 and strengthens the conclusion that strong Lyα emission may probably not be typical of high-redshift (young?) galaxies, except in some extreme cases.

Another interesting output of such studies is the hope of deriving the age of this galaxy. With only optical data this is not possible as the spectrum corresponds in the rest frame to a spectral range characteristic of the presence of very recent star formation. One should add some infrared data. Ellis (1990, private communication) claims to have detected the arc in K, corresponding to 6800 Å in the rest frame, but its $R-K$ color index corresponds to a source bluer than any galaxy ever observed! This can give a good opportunity to evaluate the spectral content of this distant field galaxy and possibly its redshift of formation (or its age).

3. THE ARCLET A5 IN ABELL 370 AND THE SPLIT ARC IN Cl 0024+1654

3.1. *Presentation of A5*

The first detection of the so-called arclets in the core of A370 was published in Fort et al. (1988). These structures are very blue and faint objects located at a distance ranging from 30″ to 1′ from the cluster center and tangentially elongated with respect to the overall symmetry. Six of them were detected in A370 and referenced as A1 to A6. The arclet A5 is spectacular in the sense that in 1987 it was the brightest and the most distant one (56″ from the center) with a large elongation of 9″. Our interpretation of these structures is that we are observing gravitationally distorted images of very faint and distant galaxies located behind the cluster center and belonging to the population of very faint and blue galaxies observed by Tyson (1988) in deep blank fields. Even if this interpretation was the most satisfactory one and if other distorted objects were found in many rich clusters (Tyson et al. 1990; Pello et al. 1991; Fort et al. 1990; Ellis, Allington-Smith, & Smail 1991), no redshift measurement was obtained for these objects, because of their very low surface brightness. That is partly why the redshift determination of A5 became also a challenge in order to confirm its origin.

3.2. *The Data*

The photometric data has been published in Fort et al. (1988). As for the arc in Cl 2244−02, the surface brightness of A5 was recalculated with great care, in order to have an homogeneous sample of measures for all the arcs. The results are displayed in Table 1.

The spectroscopic data were collected during two runs at ESO (1988 October 6–10 and 1989 September 27–30) with EFOSC in the long-slit mode (1″.5 aperture) and the B300 grism (Table 2). For each run, four frames of 4500 s each were co-added, resulting in an integration time of 2 times 6 hr. Again such a large integration time was necessary to have a S/N ratio on the spectrum high enough to perform a correct spectral analysis, and the identification of spectral features with an object whose surface brightness is about 7% of the sky brightness. But in this case a long slit was more useful than a curved slit because the shape of A5 is nearly linear and the sky subtraction was noticeably improved. Data reduction was performed with standard procedures similar to the ones applied on the arc in Cl 2244−02. The useful spectral range for these spectra is 4000–7000 Å, and the S/N ratio of the resulting spectrum is about 6 in B, 8 in V, and 7 in R. Again we deal with low S/N data in spite of the spatial dimension of the structures.

3.3. *Spectral Analysis*

In view of this spectrum (Fig. 3), the first obvious result is the lack of any emission line, and the flat shape of the continuum compatible with the slightly redder colors than the arc in Cl 2244−02. Its blue part does not increase with respect to the red range, indicating a probable lower redshift. As a minimum hypothesis, the lack of either an emission line or a break in the continuum distribution suggests a redshift larger than 0.9 (no [O II] λ3727 line and no λ4000 break) and smaller than 2.1 (no Lyα line; see Fig. 5 for the allowed domain). To determine a possible redshift we had to use the absorption lines present in this spectrum and to identify them with lines corresponding to a redshift ranging from 0.9 to 2.1. We used the same technique as for Cl 2244−02, by superposing the two spectra taken during two different runs and by identifying the most significant features which are seen on both and which are far away from the strong sky emission lines. We found five features fulfilling this condition, which are listed in Table 4. The list was then cross-correlated with a list of typical absorption lines

TABLE 4

MAIN LINES DETECTED IN THE SPECTRUM OF THE ARC IN A370 (A5)

Line	λ_0	λ (observed)	z
Zn II, Mg I	2025.5	4666	1.303
		4825	...
Fe II	2382.8	5494	1.306
		6052	...
Mg II	2796.4, 2803.5	6456	1.307

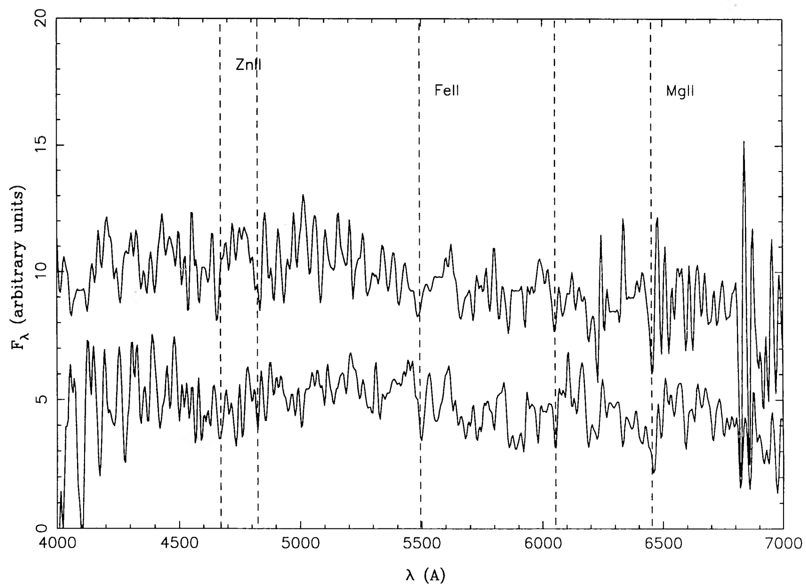

FIG. 3.—Two independent spectra of the arclet A5 in A370, obtained at ESO with the B300 grism during two different runs, the first one in 1988 (*bottom*) and the second one in 1989 (shifted upward by 5 units for clarity). All spectral features which are detected on both are plotted, with their identification with stellar absorption lines redshifted at $z = 1.306$ when possible. Both spectra are flux calibrated in F_λ in arbitrary units.

derived from Morton et al. (1988). We included a rough weighting corresponding to the values of the spectral ratios between the lines (normalized to 10,000 for Lyα) indicated by the authors. In fact these ratios were calculated from absorption lines in QSO spectra and consequently are mainly due to the interstellar gas present in absorbing systems. In our case the contribution to the absorption features is due to the stellar content of the galaxy. So the ratios could be somehow different from those of the list, but the identification of the lines is still valid. The best fit between the two tables was obtained for a redshift $z = 1.306$ in which the most prominent line at 6456 Å is identified with Mg II λ2800. If this redshift is correct, the rest frame spectral range of our spectrum is 1730–3030 Å, a spectral range where we know that there are no strong absorption features. Among our five lines, three can correspond to this redshift, and they also correspond to the most significant lines expected in this spectral range, that is Mg II λ2800, Fe II λ2383, and Zn II λ2026.

Although the absorption lines observed in the spectra are in favor of a redshift of 1.306 for this arc, this conclusion cannot be considered as definitive. At least three questions should be addressed which at present have no answer:

1.—If the observed lines really correspond to Mg II, Fe II, and Zn II, why is Fe II λ2600 not detected? The strength of this line is expected to be the same as Fe II λ2582 (Morton et al. 1988), and there is no physical reason which could explain why the second one is observed, whereas the first one is not. Actually unless Fe II λ2600 is embedded in a noisy zone of the spectrum, its no–detection is a tricky point against our identification of a redshift 1.306. But if this value is correct, the line should be observed with better signal-to-noise data.

2.—At a redshift of 1.306, no strong lines are expected at 2092 and 2625 Å, so what are the features detected at these wavelengths? It is well known from observations of nearby galaxies in the UV that many unidentified lines exist in the UV range. Therefore we suggest that these lines could correspond to such unidentified features.

3.—Even if the redshift we suggest seems reasonable, what is the probability that we deal with spurious events only due to random noise? Using simple and rather conservative assumptions, it is straightforward to show that the probability for such events to occur is about 0.1 or more. However, the probability that these three lines correspond to a given redshift between 1 and 2.1 as expected from the continuum shape and the lack of emission lines is much smaller, although difficult to estimate.

The remarks given here clearly demonstrate that definitive conclusions about the redshift of A5 are irrelevant at present. We ascertain, however, that this arc is an image of a background galaxy at a redshift between 1 and 2.1. Furthermore, if the redshift is 1.306 as indicated by the three absorption lines, then Fe II λ2600 should be detected at 5996 Å on better signal-to-noise data or Lyα at 2805 Å. But, more easily, we strongly suggest trying to detect the [O II] λ3727 line which should be at 8595 Å, a wavelength attainable with a very good red spectrograph and a low-noise CCD. IR imaging could be another possibility, since the 4000 Å break is predicted to be at $\lambda = 9230$ Å. In that case the main difficulty would be to detect such a low surface brightness object in this wavelength range. In any case further confirmation of this redshift is absolutely necessary.

3.4. *Discussion*

If we believe in this redshift determination, it is the second arc with a measured redshift inside the same cluster. This leads to some important implications, one concerning the gravitational lens situation in A370, and the other one dealing with the spectral content of a galaxy at $z = 1.306$.

This is the first time we find a gravitational lens strong enough to be able to distort with a large factor at least two different objects with different redshifts ($z = 0.725$ and 1.306). It is interesting to note that the value of the redshift of A5 was surprisingly well predicted (even with a large possible range) from two theoretical approaches. For example, Fort et al. (1988) estimated from the $B-R$ color index and with comparison to evolutionary models (Guiderdoni & Rocca-Volmerange 1987) that the redshift of such an object should be between 0.8

and 1.3. Moreover, the simulations performed by Grossman & Narayan (1989) on the overall lensing configuration of A370 including the giant arc and all the arclets suggested again that the redshift range for A5 was between 1.2 and 1.5. These arguments were not definitive conclusions, but they all seemed to indicate that if this structure is a gravitationally distorted background galaxy, it is reasonable to expect a redshift of about 1.3, the dependence of the scaling factors in the lensing configuration being small for larger values.

We tried to use the redshift of A5 ($z = 1.306$) to improve the models we suggested for A370 in Mellier et al. (1990). It consisted of an elliptical potential, similar to those of Grossman and Narayan, or a bimodal potential where the giant arc was fitted by the distorted image of a spiral galaxy at $z = 0.725$. As expected this did not improve the model at all: once the giant arc is fitted, one can always find a position (X, Y) in the source plane at $z = 1.306$ which matches the observed arclet A5 both in position and shape. This obviously means that a large number of arclets distributed all over the field would be more efficient than a single giant arc for lens modeling and potential reconstruction. The spectrophotometry of the brightest ones is a more promising tool to study the spectral evolution of very distant galaxies.

Concerning the study of this galaxy at $z = 1.306$, we can use a similar argument as for Cl 2244−02 to estimate the magnitude the source would have without gravitational magnification. Here the magnification factor is about 7 (± 2), and consequently the true apparent magnitude of the source is around $B = 24.4 \pm 0.4$, a value similar to the one for the source of the arc in Cl 2244−02. The absolute magnitude of the source is $M_B = -20.0 \pm 0.4$ for $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ and $M_B = -20.8$ for $q_0 = 0$, again evaluated with $(k + e)$-corrections taken in Rocca-Volmerange & Guiderdoni (1988) for an Sc galaxy: $k = +0.80$ and $e = -1.30$ if $q_0 = 0.5$, $k = +0.98$ and $e = -1.33$ if $q_0 = 0$. The uncertainties in the $(k+e)$-correction are about 0.3 mag, much smaller than the uncertainties due to the cosmological parameters H_0 or q_0 in the determination of the distance modulus. In any case, one should note that the source of A5 is 1 mag fainter than the source of the arc in Cl-2244-02.

The flat spectral content of the galaxy in our wavelength range (1700–3000 Å in the restframe) is also an interesting result because it suggests that the UV flux is dominated by A stars. We can estimate that the galaxy has undergone a burst of star formation about 1 Gyr before but is not presently in a stage of strong star formation. Could this result suggest that galaxies evolve through a set of starbursts instead of a continuous evolution? It is presently hard to answer such a question, but an extensive study of the arcs could give arguments in favor of such an hypothesis. Moreover some deep IR-imaging in the K band was obtained by Aragón Salamanca & Ellis (1990) up to a limiting brightness $\mu_K = 21.7$. Their nondetection of A5 imposes an upper limit for the color index $V-K$ of 3.7. Including the value of the redshift determined above, this corresponds to a wavelength in the rest frame of 9500 Å where the observed flux is extremely low. This result is consequently contradictory with the spectroscopic data and raises some difficulties about the star formation history of this peculiar object. More data are needed to get some more quantitative conclusions, especially photometric color indices in the near-infrared (R, I, J, and K).

3.5. *The Split Arc in Cl 0024+1654*

Some attention can be given here to our preliminary spectroscopic data on the arc in the cluster Cl 0024+1654 (Koo 1988). It is a complex system consisting of one large arc split into three pieces to the northeast from the cluster center, and of a smaller counter arc to the southwest. Figure 4 shows the spectra of the four arclets which encircle the cluster center that we obtained at ESO with EFOSC and a special aperture plate punched with PUMA2 (1989 October). Neither emission nor absorption lines are visible after a total exposure time of 6 hr, and only limits on the redshift can be derived from the nondetection of [O II] $\lambda 3727$, the 4000 Å break, or Lyα: $1 < z < 2.1$. The positions of the four arclets as well as the roughly similar shapes of their spectra strongly suggest that we are observing four split images of the same source located very close to the line of sight behind the cluster center.

4. DISCUSSION

We already underlined that an arc survey is a powerful method for selecting high-redshift galaxies (HRGs) which are *not necessarily* of high intrinsic luminosity like giant radio galaxies, active galaxies, or quasar hosts. Indeed, the spectral content of the sources of the arcs appears quite different from that of radio galaxies, even found in sub-mJy catalogs.

Table 5 summarizes all available spectrophotometric data (i.e., both magnitudes and redshifts) on gravitational arcs. The magnitude of the source is that of the arc, accounting for the magnification factor γ, approximated by the ratio of the arc area by the typical area of a distant galaxy (with a radius of about 1″).

The fact that all the apparent magnitudes of the arc sources in Table 5 are in the range 24–25 can be understood quantita-

TABLE 5

SUMMARY OF BASIC DATA AVAILABLE ON ARCS FOR WHICH A SPECTRUM IS AVAILABLE

Number/Cluster	B	$B-R$	μ_B	γ[a]	$B_{\rm source}$	$z_{\rm Cluster}$	$z_{\rm Source}$
1 A370 (giant arc)[1]	21.1	1.97	24.6	12	23.8	0.374	0.725
2 A370 (A5)[2]	22.3	1.05	25.4	6	24.5	0.374	1.306
3 Cl 2244−02[2]	21.4	0.77	25.3	20	24.7	0.329	2.237
4 A2390[3]	21.9	1.98	25.3	12	24.6	0.231	0.913
5 A963 (North)[4,5]	23.6	≈0.5	25.5	4	25.1	0.206	0.77
6 A963 (South)[4,5]	22.3	≈0.7	24.8	10	24.8	0.206	?
7 Cl 0024+17 (arc 3)[2]	≃23.5	≈0.7	≈25	4	24.5	0.390	>1

[a] γ is the magnification factor for each arc.

REFERENCES.—(1) Soucail et al. 1987; (2) this paper; (3) Pello et al. 1991; (4) Lavery & Henry 1988; (5) Ellis et al. 1991.

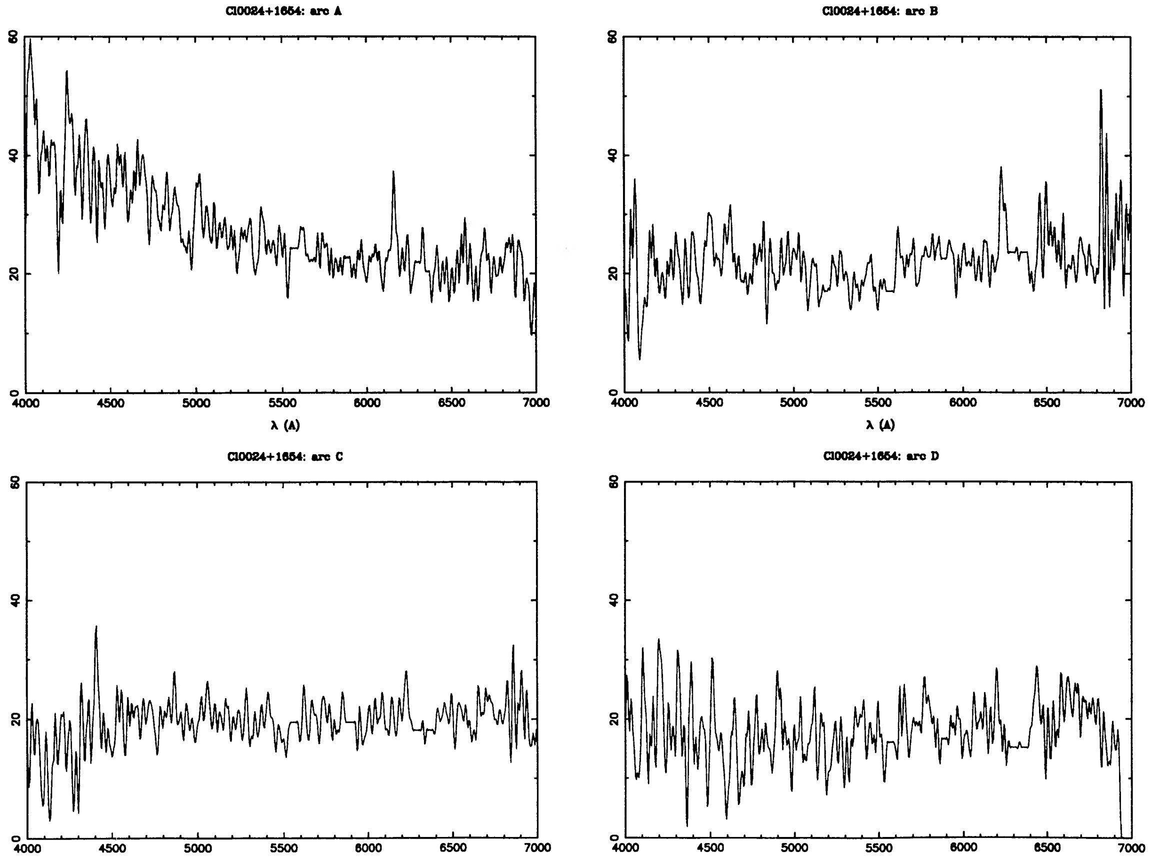

FIG. 4.—Spectra of the four arclets in the cluster Cl 0024 + 1654 obtained at ESO with the B300 grism. The total integration time is 6 hr. Arc is split in three arclets to the northeast from the cluster center, referred to as " A," " B," and " C " (from north to south). D is the fourth arclet, to the southwest from center. A and D are more blue, probably due to contamination of B and C by superimposed faint cluster galaxies. All spectra are flux-calibrated in F_λ in arbitrary units.

tively. Indeed, the typical width of the arclets is about 1", and their B surface brightness is limited to $\mu_B = 25.5$, corresponding to a continuum flux equal to 5% of the dark sky brightness: it is the minimum value of the flux for which we can expect to reach a S/N ratio of 10 in low-resolution spectroscopy ($\Delta\lambda \simeq 20$ Å) in about 10 hr of integration time with present-day large telescopes.

These data are plotted in a redshift-magnitude diagram (Fig. 5) and compared with the current deep redshift surveys. However, it does not make sense to compare the rough numbers of objects in each redshift range since they strongly depend on the sky coverage of the surveys and on redshift effects (discussed below).

Taking into account the different sampling rates for each field, Broadhurst, Ellis, & Shanks (1988) sampled an effective area of 1075 square arcmin. (for about 200 redshifts). The LDSS survey (Colless et al. 1990) had a coverage of 101 square arcmin. (for about 90 redshifts). It is difficult to estimate the corresponding area of our preliminary arc survey, which is by no means complete. But a first limit can be derived from the position of A5 at 56" from the cluster center. Its elongation of a factor 6 most probably corresponds to the position of the source at a typical radial distance of 20" in the source plane. We take this value as the maximum radius in which one expects to produce a large arc. Up to now, probably less than 50 rich clusters of galaxies having the critical mass density have been surveyed to the limiting magnitude corresponding to the typical arc brightness (see Table 5). Thus we can roughly estimate that the total sky coverage equivalent to the arc survey is typically around 20 square arcmin in the source plane, a factor 5 lower than the LDSS area, for five redshift determinations. So, it is likely that at least 20 galaxies of magnitude $B \simeq 24$–25 and of redshift $z \simeq 0.7$–2 could be found on a full survey corresponding to the LDSS area.

Preliminary data from Lilly, Cowie & Gardner (1991) up to the magnitude $B = 24$ give a mean redshift around 0.35 in the range $23 < B < 24$, and they do not find evidence for a large population of galaxies at redshifts larger than 0.5. On the contrary, all our sources correspond to HRGs in the magnitude range $24 < B < 25$. It is the magnification which allows us to go at least 1 mag deeper than any other method. Figure 5 suggests that a significant fraction of the galaxies whose magnitude is around 24–25 is at large redshift. It is of course a first step toward the analysis of the redshift distribution of the very faint population. However, our sample has some peculiar characteristics and some possible section bias that it is necessary to consider.

1.—To produce an arc, or to have a distortion high enough to be detectable (axis ratio larger than 3 typically), the sources must be at some minimum distance behind the lens (the cluster). For various reasons, we look for faint objects with high axis ratio in preselected clusters of redshift 0.15–0.5.

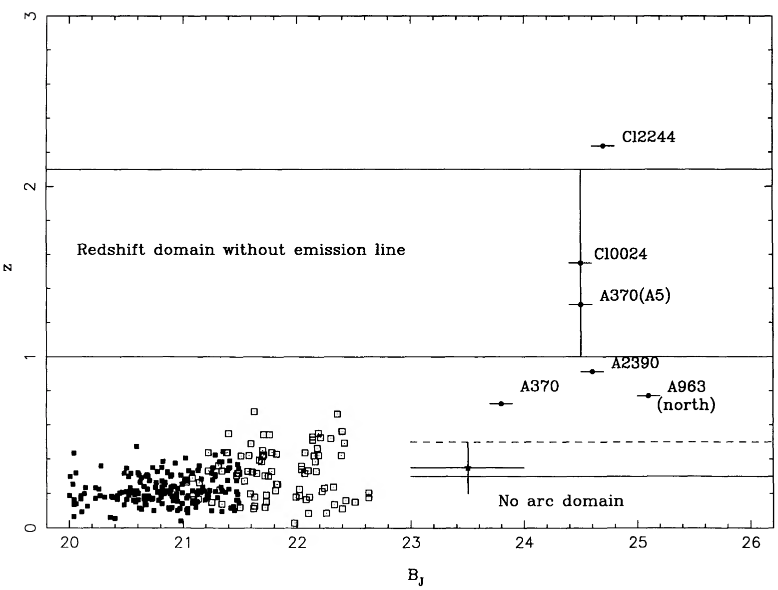

FIG. 5.—Redshift vs. apparent B_J magnitude is plotted for the sources of the arcs (Table 5) and for the galaxies from two spectroscopic surveys: Broadhurst et al. (1988) (*filled squares*) and Colless et al. (1990) (*open squares*). Additive cross represents the preliminary data of the deep Hawaii survey (Lilly et al. 1991). Note the allowed redshift range corresponding to the absence of emission lines in the spectra of the four arclets in Cl 0024+1654. Arc redshifts smaller than 0.3 cannot be found since our survey only concerns clusters with redshift $z > 0.15$ (*full line*). Accounting for the mean redshift of the cluster sample, $\simeq 0.25$, most arc redshifts are actually expected above the dashed line ($z = 0.5$).

The minimum redshift of the source depends on the cluster distance (and on its mass concentration), but it must be typically larger than 0.7 in most cases (Blandford & Kochanek 1987).

2.—Due to the low surface brightness of the arcs, which makes it difficult to detect absorption lines, some redshift ranges cannot be found simply because the expected emission lines, either [O II] $\lambda 3727$ or Lyα, are too close to a sky emission feature or fall out of the visible range. On the contrary, some other redshift ranges are favored since an emission line falls in a region free of sky features. This limitation occurs for other kinds of samples of HRGs.

3.—In the general context of the detection of arcs in deep CCD images of clusters, the arcs seem to be more easily detected in the blue (U or B filters) where the contamination of the red envelopes of the cluster galaxies is smaller. There is no theoretical reason to detect only blue arcs, and it is not an absolute observational rule since a few of them in our survey are rather red (see, e.g. the arc in A2390 in Pello et al. 1991). But note that this is still a point to be clarified: Grossman (1990) mentions observational evidence for the existence of distorted galaxies which are red in $R-I$. Indeed, our preliminary results of an ultradeep survey in the I filter of clusters with arcs confirm that this is the case only for a few arclets.

These selection biases are rather different from those encountered in samples based on quasar absorption lines. These two methods appear complementary to discover very distant "normal" field galaxies and to understand the primeval evolution of ordinary galaxies.

This observing program is at the limit of present-day instrumentation, and it needs a large amount of telescope time. The next generation of very large telescopes is particularly well suited to such surveys which will be achieved much more efficiently. We will also learn a lot from IR imaging of the arcs in which the redshift is determined for the study of the continuum flux distribution of distant galaxies on a large wavelength range. Especially with the near-IR photometry (I, J, H, and K bands), one should expect to have information on the oldest stellar population in galaxies at redshift larger than 1, and that should be used for dating such objects and for constraining the models of galaxy formation.

We wish to thank J. Bergeron, C. Lawrence, and E. Turner for helpful discussions and encouragement at the starting point of this spectroscopic survey of arcs. We also are grateful to our collaborators from Toulouse Observatory (J. F. Le Borgne), the Universitat de Barcelona (R. Pello and B. Sanajuja), Bell Labs (T. Tyson and his group), and Durham University (R. Ellis, A. Aragón Salamanca, and I. Smail) who provided us with some IR data on the arcs before publication.

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