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Letter to the Editor

Detection of a distant cluster in the center of the shear field in Q 2345+007

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Abstract. We report on the detection of an excess of faint blue galaxies located in the center of the shear field detected by Bonnet et al. (1993). By using ultra-deep B and I CCD images obtained at the prime focus of CFHT, we computed isopleth contour maps by color intervals and found an excess of blue galaxies exactly centered on the center of the shear field (found by Bonnet et al.), with a small additional clump close to the double quasar. The angular size of the region with the density excess, as well as the color and surface brightness of the galaxies are evidences that we have detected a cluster of galaxies at redshift larger than 1. The faint blue galaxies are not distorted (no detectable shear) as expected for a lens responsible for the shear pattern. We discuss the consequences on the distance of the faintest sheared galaxies and on the usefullness of the weak shear technique for cosmology.

Key words: Galaxies: Clustering – Photometry – Evolution Gravitational Lensing – QSO statistics

1. Introduction

Bonnet et al. (1993; hereafter paper I) reported on the discovery of a coherent weak shear in the field of the doubly imaged quasar Q2345+007, and a faint arc with a center of curvature corresponding to the center of the shear field. They argued that both effects are due to a massive, although invisible cluster-like structure, off-centered of about 1' from the double quasar. This hypothesis could explain the large angular separation of the two images which confirms the gravitational lens hypothesis for the quasars Q2345+007.

Although they do not reject the hypothesis that the shear in Q2345+007 is due to a "dark cluster", we cannot exclude that it is associated with a large structure which is visible but too faint to be easily detected from our observations. The first images used in paper I are not very deep, and they could only marginally detect an excess of galaxies in the center of the shear field. We then reinvestigated this field, and in this Letter we analyse our new ultra-deep CCD images Q2345+007 in the B and I bands. We report on a clear excess of faint blue galaxies with $B - I \leq 1.2$.

In the first section we describe the CCD observations and data reduction and the possible detection of some new gravitational images. The second section is dedicated to the detection and the characteristics of the distant cluster, and on the evidences that it should be the lens responsible for the shear. In the conclusion we discuss some cosmological implications of our results.

2. Observations and data reduction

Ultra-deep CCD exposures in the blank fields were obtained at the prime focus of the CFHT in oct 1992. The CCD was the RCA2 640×1024 binned 2×2, which corresponds to 0.4"/pixel and a total field of view of 2.1'×3.4' sqarcmin. The seeing was good (0.8"), but badly sampled and these images are therefore not suited for measuring the shear. The exposure times were much longer than in our previous images: 4.5h in the B band and 4h in I, both with the RCA2 CCD. All the data have been processed using the IRAF/FOCAS package. Due to the presence of a very bright star close to the field, we could not suppress all the residuals on the flat fields, even by using the superflat. The diffusion of this star induced a large scale pattern oriented from the north-east to the south-west which slightly perturbed the magnitudes and color indices of individual galaxies. We then took great care to eliminate the residuals in both bands by using an analytical fit of the diffusion pattern. This correction was efficient because the star only induced a background variation on scale larger than the CCD, which can be easily modelled. The final IRAF/FOCAS catalogues give galaxy parameters for objects as faint as $B = 28.5$ and $I = 26.5$, but our completeness limits are $B = 27$ and $I = 25$ respectively. The photometric errors were estimated by using simulated images of faint galaxies (Bonnet 1994) from which we computed the magnitude differences between the simulated objects and the final FOCAS catalogue. We also estimated the error by analysing the stability of the magnitude computed with FOCAS with small changes in the input parameters (for instance limiting isophotes above the sky background). We checked that the accuracy is at least 0.15 magnitudes up to the completness limits of the B and I bands, but it is rapidly getting worse above these limits. For the faintest objects, the accuracy is smaller than 0.5 magnitudes.

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LETTER 1994A&A...285L..15M

The deep B CCD image is shown on Fig.1. Many very faint objects are detected. We draw attention on the sharp elongated structures located close to the double quasar. It is formed of two distinct objects (referred as B and D) with axis ratios of 5 and 2.7 respectively. We suspect we are observing a merging gravitational pair, exactly as the pair $B2$ and $B3$ in A370 (Kneib et al. 1993). It is remarkable that the orientation of these two objects is similar with the orientation drawn by the double quasar. The $(B-I)$ color of each component are $(B-I)_B = 2.1 \pm 0.5$ and $(B-I)_D = 1.5 \pm 0.7$. The B surface brightness of the central peak of B is $\mu_B = 27.34 \pm 0.35$ mag/arcsec^2, and $\mu_B = 27.68 \pm 0.5$ mag/arcsec^2 for D. These data seem only marginally compatible with what we could expect if these objects were doubly imaged of a single source. However, they are faint, badly resolved, and contaminated by the light of the double quasar and by two nearby faint objects as well. So the photometric data cannot be used to firmly reject the gravitational pair hypothesis.

3. Evidence for the detection of a distant cluster

3.1. Evidence of a blue excess of galaxies

The deep B images show an excess of faint objects around the center of the shear field computed in paper I and a small excess close to the double quasar. We quantified its significance level by producing a set of isopleth contours maps of the B frame by color interval. Such color filtering allows a good photometric detection of a gravitational structure formed by similar galaxies. At low and intermediate redshifts, cluster galaxies concentrate in a thin color-magnitude strip which make these clusters easily detectable from a color filtering (Mazure et al. 1988) of red galaxies. On the other hand, photometric evolution models of galaxies show that the colors of distant galaxies have a small dispersion (see Koo, 1990 for instance) and concentrate toward very blue colors, provided their redshift exceeds 1. Very distant concentration of blue galaxies should be also detectable by using our filtering.

We plot galaxies belonging to the B and I complete samples with various $B-I$ color indices ranging from 0 to 3.5, in order to have an optimal visibility of any structures. In all cases but one, the signal was weak and poorly significant, and we believe they were only random fluctuations; in particular we did not see any correlation between the (removed) residual pattern due to the bright star and the spatial distribution of red objects. This proves that our correction was fairly accurate for this purpose. However, a strong signal was detected for the bluest galaxies. It is maximum for $(B-I) < 1.2$. The excess of these blue objects is exactly located at the center of the shear field. Furthermore, a second signal is also detected, within the same color interval, close to the double quasar. The first isopleth peak is almost circular, with a small extension toward the North-East direction. The peak of the density is 5 times the averaged value of the total B field. We arbitrary estimated its extension by computing the angular radius at which the density drops to 2.5 times the background value. Within this radius (25") we found 26 blue galaxies, against 146 such galaxies in the all field. The significance of the excess within 50" is computed as follows: $((N(50")- < N > (50"))/\sigma(50")$, where $< N > (50")$ is the averaged density within a circle of 50" diameter computed from 146 objects in the total CCD area, and $\sigma(50") = \sqrt{< N > (50")}$. It reaches 4.5σ and even 18σ at the peak. The conditional probability to find randomly a 4.5σ increase centered on a given point and within an error box of 50" (which is an overestimated uncertainty on the center position of the shear field) is $5 \times 10^{-5} \times 50" \times 50"/S_{CCD} \approx 5 \times 10^{-6}$ in case of independent events, where S_{CCD} is the total area covered by the CCD. Our finding is therefore highly significant. The circular region corresponds to a diameter of 50", or 400 kpc for z=1 (assuming $\Omega = 1$ and $h_{50} = 1$). But, the most elon-

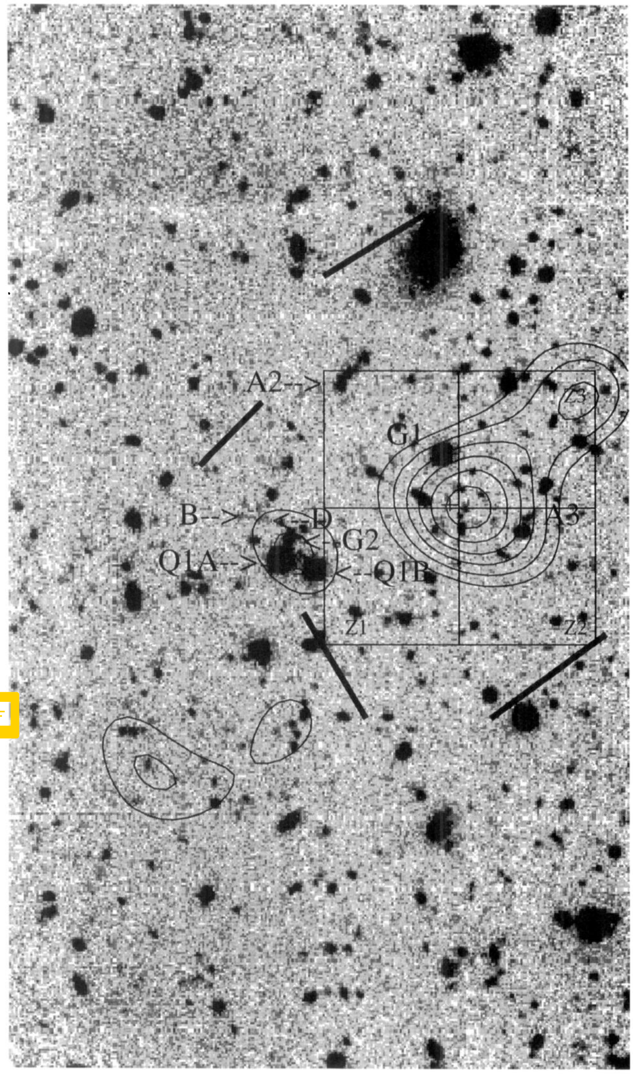

Fig. 1. Deep B CCD image taken at the prime focus of CFHT. The double QSO (Q1A and Q1B) and the arc A2 reported in paper I are visible. The faint extension located at the upper right of A2 is probably another object (see paper I). The thick lines show the averaged orientation found in paper I. The contours show the isonumber density of galaxies with $(B-I) \leq 1.2$, $B < 27$ and $I < 25$. The most extended contour corresponds to 2.5 times the averaged density of the field. The center of the shear field reported by Bonnet et al. is indicated by a cross close to the center of the isocontours, between G1 and A3. A3 is a weakly elongated object that could be a counter image associated with the arc A2. Note also the elongated structure (B-D) close to the double quasar (just above the double cross). It could be a typical case of merging image. The square is the area where the orientations of the blue objects was computed (see section 3.2)

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1994A&A...289L..15M

gated axis extends on 74", or 600 kpc. These dimensions are compatible with the typical sizes of an inner region of a rich cluster of galaxies. The galaxies belonging to this structure have an averaged size of 1.1" ((8kpc at z=1, $\Omega = 1$, $h_{50} = 1$), an averaged magnitude of 25.9$\pm$0.9 (this is not trully the error, but the one σ level dispersion on the average) and a surface brightness of 26.9 ± 0.8 mag/arcsec^2.

The photometric data, as well as the angular size of the structure suggest that we are observing a very distant gravitational lens. In order to confirm this we compared the color of these galaxies $(B - I) < 1.2$ with those predicted by the Bruzual and Charlot's models for a given redshift. Since we only have one color index, we looked at all cases of evolution and non-evolution models for galaxies (from elliptical to irregular) and took care to have a conservative attitude: instead of selecting redshift ranges compatible with data, we rather checked whether some redshift ranges could be definitely eliminated. In all cases, but one, the models preclude redshifts smaller than one. And for the single exception, the redshift is below 0.2, which does not seem compatible with the small size and faint surface brightness, unless we assume it is a clump of low surface brightness dwarf galaxies. We conclude that the density peak is made of galaxies at redshift larger than one.

The density peak located close to double quasar is smaller than the one around the shear center. Only 8 galaxies are bluer than $B - I = 1.2$, but the galaxy excess can be seen by eye anyway. The shape of the clump is elliptical and reach the 2.5 contour level at a typical radius of 15", or 155 kpc. But the significance level at this radius is 7σ which is very high. The galaxies have the same characteristic as those observed in the other clump (same averaged size, magnitude and surface brightness). It is possible that this is a faint extension of the structure responsible for the shear. Indeed, the double QSO Q2345+007 could be a rather complex lens!

3.2. Evidence that these galaxies are not sheared

If the density peak show the lens responsible for the shear field detected in paper I, then obviously the blue galaxies located in the peak are not sheared. This can be tested easily by looking at their orientation, which is expected to be randomly distributed. On the other hand, if we are wrong, they should be sheared as any background galaxies, and then must have preferential orientations, either orthoradial, or radial with respect to the shear center. We checked this point by comparing the orientation of the blue galaxies around the density peak to the orientations of the galaxies outside the area represented on Fig.1, where we know that the shear is present, and where we expect preferential orientations, with a strong deficit of galaxies with an orientaton of zero degree (with respect to west-east axis, counter clockwise positive). We computed the orientations by using the IRAF package and we plotted the cumulative histogramme of orientations for the four fields (Fig.2). We clearly detected a deficiency of galaxies with a 0 degree orientation, and a slow but continous increasing number of galaxies with orientations ranging from 10 up to 90 degrees. This that the orientation of the shear measured by a more sophisticated technique can also be detected by IRAF (note that we discarded the ellipticity parameters because of the poor sampling of the data). We then applied the same technique for the blue objects near the central peak. Since it concerns the central region of the lens, we expect to observe radial shear. Generally, the crowding by bright central cluster galaxies makes radial shear undetectable in practice. But in the present case, we do not see any foreground galaxies but the blue ones, and consequently we can measure accurately the orientation of these faint galaxies. We first divided the central region in four sub-areas with respect to the center, then making a histogram for each (Fig.2). We did not detect any significant excess nor deficiency of orientation for any angle. We also computed the angle difference between the orientation of the galaxies and the orthoradial direction. In case of sheared object this angle should be close to 0 degrees (if the shear is radial) or 90 degrees (if orthoradial). Again we did not detect any preferred direction but a pure random distribution of orientation. This result is particularly relevant and statistically meaningfull because we are near the center of the lens and shear should be rather strong. So we confidently conclude that the galaxies of the density peak are not sheared. This is the second evidence that we probably detected the lensing agent.

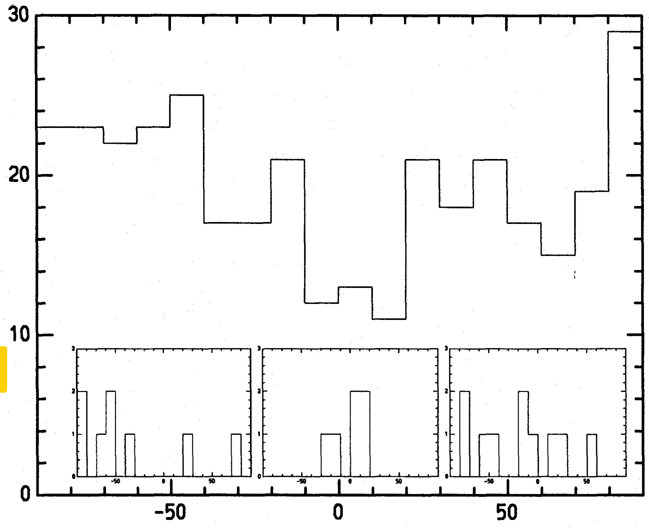

Fig. 2. Histogram of orientations of the galaxies in the comparison fields (large panel) and in the density peaks (small panels inside). The small panels represent the histogram of orientation of the sub-area $Z1$ to $Z3$ showns on Fig. 1. The expected orientations were -45^0, $+45^0$, and -45^0, with a small dispersion, which are not seen on the histograms. Field $Z2$ seems to have preferentially galaxies with 0^0 orientations, but this is not statiscally significant. Furthermore, this value is not expected for radial or orthoradial shear. The comparison field clearly have a deficit of zero degree oriention, whereas the density peak not. This shows that the galaxies are sheared outside the dense region and not sheared inside. This is what we expected if these galaxies belong to the lens responsible for the shear.

4. Discussion and conclusion

We have given observational evidences that we have detected the gravitational lens which is responsible for the shear field, and the arc occurence in the field of the double quasar Q2345+007. Similar results have been recently found by Fisher et al. (1994). This shows that faint cluster lenses can also be

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1994A&A...289L..15M

found in the B-band. The lens seems at $z > 1$, but we cannot give a secure upper limit of the redshift from our observations. However, for a QSO at redshift 2.2, the upper limit for the lensing agent for having a cluster critical mass density large enough to form arcs such as $A2$ is $z_{max} \approx 1.8$. Although the lens is complex, many observational data are now available that could be used to give a good model of the multiply imaged QSO (the galaxy $G2$, the shear pattern, etc...).

We have no spectroscopic evidences that the deflector is at $z > 1$. But in paper I we already argued that the weak shear pattern observed in this field is compatible with a cluster of galaxies with a typical velocity dispersion of 1000 km/sec, located at a redshift of about 1. Furthermore, the galaxies we have detected may be also responsible for the absorption lines detected by Tyson et al. (1983) in the spectra of the double quasar. In that case it could be that the lens is at a redshift of 1.4. The consequence of this is that a subtantial amount of faint background galaxies must be at a redshift higher than 1.5. This is an interesting result because the shear measured in paper I is computed from the shape parameters of the *faintest* galaxies detectable, and therefore it could be an evidence that there may be a gap between the distance of two types of galaxies: on one hand those measured from the faintest redshift surveys ($B < 24$), and from the "brightest arclets" (B from 25 to 27; Kneib et al. 1994), and on the other hand the distance of the faintest sheared galaxies reported in this Letter which range between $B = 27$ to $B = 28.5$. Ellis (1992) already suggested a new population of distant galaxies in order to reconcile the faint spectroscopic surveys and the deep galaxy counts from Tyson (1988). In this case, the faintest end of the blue Tyson's population would actually be at redshift larger than 1.5. Note that the redshift value found here for the faintest sheared galaxies is high but (marginally) compatible with the results from Smail et al. (1994) and from Bonnet et al. (1994) who conclude that most of faintest galaxies could hardly be at redshift larger than 1.2. But, although these conclusions are based on splendid condition, the seeing may be a crucial uncertainty. If it was confirmed, our detection would show that the gravitational shear analysis is also a well suited tool to study the redshift distribution of the faintest galaxies. Infrared photometry in the J and K bands added with our optical data in B and I should give enough constraints to infer the redshift of the lens. This work is now in progress (Pelló et al. 1994). Medium resolution spectra of the background quasars can also be done by looking at absorption lines of the lens galaxies. Another possibilty is to use narrow band filters centered on the [OII]λ3727 emission lines. If the galaxies are at redshift 1.4, we can expect that these galaxies have a strong star formation and then observe them easily at 8950 $\AA$.

The detection of the distant cluster responsible for the weak shear is a preliminary evidence that the Bartelmann and Schneider's (1993) guess is correct and that many quasars could be magnified by cluster like structures which have not been detected yet from optical or X-ray surveys. It also shows that the weak shear method is a unique tool to detect faint gravitational structures such as very distant clusters of galaxies, and even protoclusters. The detection of possible very high redshift clusters of galaxies is a challenging task which may have strong implications for cosmological scenario of structure formation. Recently, Dressler et al. (1993), Giavalisco et al. (1994) , and Kassiola et al. (1994) also reported possible discover of high-z clusters. The new important point in Q2345+007 is the detection of a cluster of galaxies at redshift larger than 1.5 which is already able to act as a strong lens (since we observe an arc). This shows that at such redshift the innermost region of clusters may already have reached a high mass density, and velocity dispersion as high as 1000 km/sec. Therefore, unless we assume that the arc was generated by a complexe multi-screen lens, we really are observing one of the densest high redshift gravitational structure yet known.

The lensing agent could be also constituted of many lenses superimposed on the line of sight. For example, perturbers like $G1$ and $G2$ (see Fig.1.) may keep the lens complex, which could change part of our conclusions about the total mass of the lens itself. Another possibility is that the faint blue galaxies we found are at a redshift lower than 0.3 ! The $B - I$ color index is compatible with some evolutionary models. Furthermore, if they are at a low redshift they are indeed unsheared because they are in front of the lens responsible for this shear! But these galaxies are all *faint* and *blue* which makes a structure with a completely new luminosity function and color distribution. Groups of faint blue galaxies has not been observed yet in any observations of nearby systems. Such configuration, which should be located exactly where we expect a distant cluster looks like an improbable conspiracy! It is therefore more reasonnable to think that we detected an excess of blue galaxies with a probable redshift larger than 1.

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