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Letter to the Editor

Detection of weak lensing by a massive dark halo in Q 2345+007★

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Abstract. We report the detection of several arclets, a small arc, and a coherent gravitational shear field centered on the vicinity of two bright galaxies, $\approx 45''$ away from the double quasar 2345+007. In addition we discovered a new QSO at $z = 2.653$ and at $\approx 2'$ from the center indicated by the shear. The shear is found from weak distortion of background galaxies and is representative of a cluster-like mass. This suggests a possibility that 2345+007 A, B are two images of the same source, split by a cluster-like mass.

The two galaxies have redshift $z = 0.28$, and the field is too poor in bright galaxies to indicate a rich cluster at this redshift. In addition, if there were a cluster-like (dark) mass at $z = 0.25$ with a critical line passing between the A and B QSO images, the shear field would be significantly stronger than what we observe.

However, deep images show a small excess of faint blue galaxies in the area on which the coherent shear is centered. Thus, it is possible that a rich cluster at a higher redshift induces the coherent shear. In this case, it would be able to produce a critical line between A and B of 2345+007.

To our knowledge, this is the first direct measurement of a weak shear near a double quasar. We find that this is a powerful technique to locate large masses on lines of sight, even where concentrations of galaxies are not previously discovered. In particular, this technique will enable us to detect hypothetical concentrations of dark matter which are not traced by galaxies. It can also provide a new efficient approach to the problem of large scale quasar-galaxy associations, raised by Fugmann (1990) and Bartelmann & Schneider(1993).

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

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★ Based on observations collected at the Canada-France-Hawaii Telescope at Mauna Kea, Hawaii, USA, and the European Southern Observatory at La Silla, Chili.

1. Introduction

The double quasar Q2345+007 was first reported by Weedman *et al.* (1982). The two images (hereafter Q1A and Q1B) are separated by 7" and the Q1B component may possibly be an unresolved double object (Wier & Djorgovski 1991). Because no obvious deflector had been observed even on deep images, Tyson *et al.* (1986) accepted the hypothesis of a lens by a massive dark halo (Narayan *et al.* ,1984). Multiple lens configurations can also explain the large angular separation of the two images (Subramanian and Chitre 1984), unless they simply come from a real pair of quasars at the same redshift (Blandford and Kochanek 1987). In any case it is a challenge to prove or reject definitely the gravitational nature of this double quasar.

In the following we relate new observations on the field, and report the discovery of some distorted objects around the nearest galaxies of the double quasar and possibly a small arc. We compute the shear field from subarcsecond seeing images that reveals the effect of a large deflecting agent. In the section 2 we detail the photometric data of the field with special attention to the two bright galaxies, point like objects which could be quasars, and arc(let) candidates. The third part is devoted to the detection of the shear effect on the field. A simple model of the lens in section 4 proves consistent with the presence of a massive deflector centered on the galaxies. Discussion and conclusions are in section 5.

2. Observations of Q2345+007

Our data on Q2345+007 come from calibration exposures on the Tyson's blank field during the Toulouse arc survey obtained at the prime focus of the Canada-France-Hawaii-Telescope (CFHT). A total of 1.5 hours in B with seeing of 0.7", 2.5 hours in I with seeing of 0.7" and additional data in the R and V bands with seeing of 0.9" have been used. The data have been processed using the IRAF software package, except for the analysis of the shear field which is described in the next section.

The deep images show a short elongated structure (A1) close to galaxy G1 (see figure 1 and 2). Furthermore, an arc-like object (A2) can be observed in the north, between galaxies

G1 and G2. The arc candidate is very faint but it is visible in the B, V, R and I frames. In the deepest images the arc looks rather patchy, so we cannot exclude a merging system or two superimposed galaxies. However, the middle segment is fuzzy, elongated and curved toward G1 as expected in the case of a lensing effect. Its curvature radius is about 20 arcsec., a deviation angle corresponding to a cluster-lens. Another arclet (A3) lies close to G2. The three arc(let)s have also elongation orthoradial to G1. Thus, marginal evidences that a massive structure could be centered on this galaxy prompt us to re-analyze the shear of background galaxies in this field. However, it is strange that the brightest galaxy G2 seems to have no influence on the curvature of A2.

Finally, spectra of the nearest galaxies G1 and G2 and of some other stellar-like objects (referenced as S objects in figure 1) have been collected at the ESO New-Technology-Telescope (NTT), in July 1993. G1 and G2 are at a redshift of 0.280 and 0.279. In addition a third galaxy at redshift of 0.280 is resolved in the wings of G1. Therefore, if a cluster of galaxies were associated with these galaxies it would be clearly visible. The object Q2 appears to be a quasar at a redshift of 2.653.

Table 1 summarizes the photometric data of all objects of interest in the field.

Table 1. Photometry of galaxies, quasars, arcs and arclets relevant for this paper.

	B	R	I	$B-R$	$B-I$	z
Q1A	19.33	18.79	18.78	0.54	0.53	2.15
Q1B	20.61	19.97	19.83	0.64	0.78	2.15
Q2	20.98	20.13	20.05	0.85	0.93	2.653
G1	20.16	–	17.41	–	2.75	0.25
G2	22.04	–	19.38	–	2.66	0.25
A1	23.37	22.30	22.09	1.07	1.28	–
A2	23.65	23.15	>24.1	0.50	2.20	–
S1	22.62	–	20.39	–	2.23	–

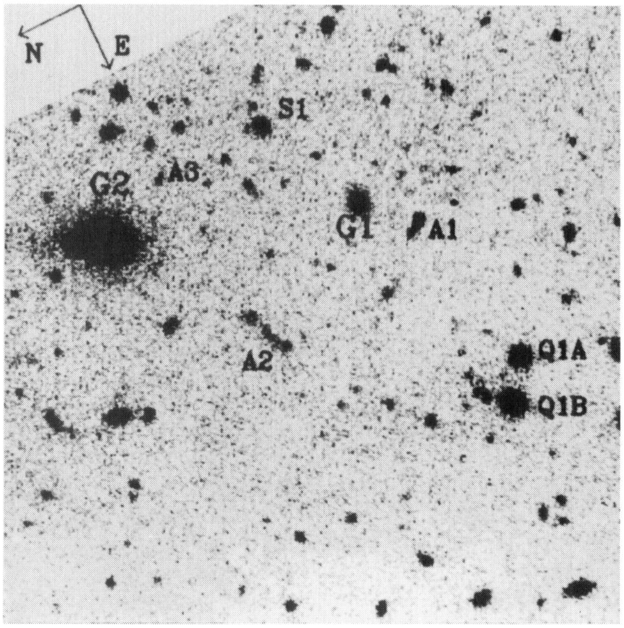

Fig. 1. B CCD image of the central region in the neighborhood of the double quasar Q2345+007. The arclet A1 is clearly visible. The curvature of A2, located between two small objects, is consistent with its gravitational nature.

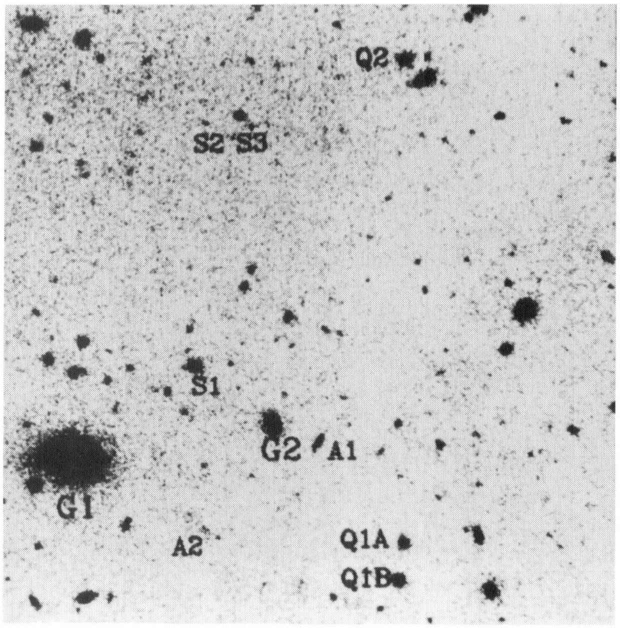

Fig. 2. I CCD frame of the blank field. The second quasar Q2 is on the right. The faint object S3 coincides to the third image of the quasar predicted by the simple model described in this paper.

3. The shear field in Q2345+007

3.1. Methodology

As it was already observed by Tyson *et al.* (1990) in A1689, a deflector producing arc(let)s also induces weak distortion on all background objects near its center. The detection of a coherent shear around G1 would definitely reveal the existence of a massive deflector and the position of its center. To visualize it we used a data reduction process developped for the detection of a coherent shear at the periphery of dense clusters (Bonnet & Mellier 1993, in preparation). Basically, the programme computes first, from a very deep image with good seeing and sampling, a catalogue of extremely faint objects. The shape parameters are evaluated from the second order centered momenta, normalised to unity matrix, computed through a constant aperture of width about 3 seeing disks. From this catalogue, other selection criteria are applied such as brightness limits, and ellipticity. The mean values of the second order momenta matrix of selected objects is then computed over small boxes on which the shear is assumed constant. Theorically this averaging process converges towards the local shear matrix and its efficiency increases if the selection is restricted to objects with ellipticity close to the one induced by the shear on circular sources.

Typically, in order to get a good convergence, one needs to add up at least 20 objects per box. When the field is deep enough, such boxes cover areas over which the shear does not vary significantly. Near the center of clusters where the shear vary quickly and the number of objects is smaller, the detection is much better by making a guess for the center's position and using radial boxes of angular size $\Delta\theta$ instead of paving the field with square boxes.

The details of the method are described by Bonnet & Mellier (1993). It is important to note that the procedure was extensively checked by complete simulated images of "lensed" and "unlensed" faint galaxies, taking into account seeing and sampling effects, photon noise, plus a wide set of parameters such as integration time, telescope characteristics, quantum efficiency, etc... The algorithm is capable of detecting instrumental problems (optical distortion, telescope tracking) as well as astronomical effects (atmospheric refraction).

For a lens at $z = 0.25$ and a high velocity dispersion, the detection of the shear is easy. As one increases z, or decreases σ, the detection becomes much more tricky. The tests with deep images of distant clusters having arcs and arclets and for which good potential modeling have been done give us confidence in our detection method and the validity of the shear pattern we derive.

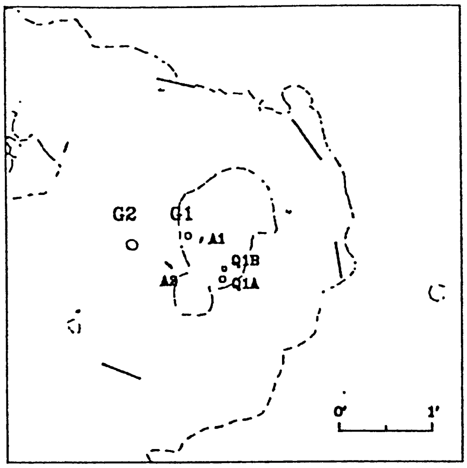

Fig. 3. Analysis of the shear field around galaxy G1 from the I image. In dashed line, 1 and 2 σ probability isocontours for the center position.

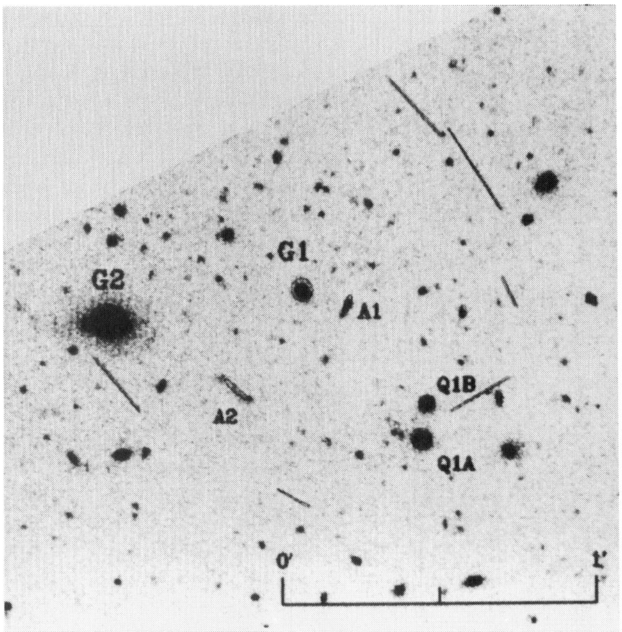

Fig. 4. Analysis of the shear field around galaxy G1 from the B image.

3.2. The shear in Q2345+007

The analysis of the distortion pattern of the background galaxies in both B and I images of Q2345+007 gives evidences of a coherent shear. No deconvolution of the instrumental plus atmospheric contribution has been performed, because we do not have star fields produced under the same conditions during observations. Nevertheless the detected signal is large enough and the typical pattern induced by telescope tracking default is not seen at our detection level. It should be emphasized that the same results are deduced from both I an B images, obtained with two different CCD cameras positionned at two bonnette angles. About 100 objects were used and gathered in groups of 20 per quadrant. The shear pattern is displayed in figures 3 and 4. The segments show the orientation of the mean objects for each quadrant. We did not try to measure exactly the shear value, as it would be always underestimated, because of: (*1*) uncorrected contamination by foreground objects, specially in area of poor numerical density, (*2*) dimming effect when the shear rotates rapidly within the quadrant. The best signal to noise ratio has been obtained when we selected objects with axis ratio ranging from 0.7 to 0.9. It is then likely that the intrinsic shear is about 0.15. The shear pattern looks similar to what simulations predict for a singular isothermal sphere at $z = 1$ and $\sigma = 1200$ km s^{-1}.

The probability to reproduce such a dispersion from random draws is below 0.2% for the I field. We have tested a grid of probability for the center location at the 2σ and 1σ confidence levels. This is consistent with a cluster mass centered on G1, but the extension of the contours shows that the position of the center cannot be computed accurately from these data. Anyway, it seems again to reject G2 as the center. Because the signal to noise ratio depends on the number of objects in the sample, the slope of iso-probability is steeper in high density regions. It then is a natural effect of the algorithm that the shape and extension of the isocontours are somewhat correlated with the number density fluctuations. Thus little can be inferred on the shape of the potential. Due to lower statistics, the confidence level falls down to 90% on the B field. This is probably due to the smaller field which prevents a good determination of the best center. Nevertheless, restricting the selection of objects on criteria of cross correlation with a B-catalogue of a previous CCD images of the field, we have been able to improve the confidence level up to 2σ, with the best center on G1 (figure 4).

The algorithm which calculates the shear can exclude the inner part of the picture to avoid possible contamination by foreground bright companions of G1 and G2. In the outermost regions the signal to noise ratio decreases radially as we would expect for a cluster-lens.

Further observations in this field should improve the analysis : first, the field of view of the B image is too small to increase the determination of the center coincident with G1 and detect wether the shear decreases with radius ; second, the I image has a larger scale but could be much deeper in order to increase the signal to noise ratio ; third, a complete catalogue up to very faint magnitudes in two colors, say B and R, would allow a better selection of background objects by using color indices, and rejecting objects for which shape parameters differ from one color to the other by more than some limits.

4. Preliminary modeling the lens Q2345+007

By using the shear pattern and the arc(let)s we have an idea of the center location of the deflecting mass. But even with the QSO positions and amplification ratio, plus the redshifts of the quasars and of the nearest galaxies, we are not in position to give a unique modeling for the lens. We therefore limit our investigation to a possible observational prediction.

The first idea is to assume the double quasar a true pair corresponding to a "fold" configuration. In this case we expect a third demagnified image on the other side of the lens which could be a constraint on the final test of our modeling. The center of the elliptical deflector was chosen at the center of G1 and we required the critical line to lie between the two quasar images. The details of the modeling technique and the analytic potential used can be found in Kneib *et al.* (1993). We assumed a single potential, the ellipticity, orientation, velocity dispersion, core radius and slope being free parameters. The modeling technique minimizes the difference between the source parameters correponding to the two images of the quasar, keeping the magnification ratio as it is observed, and by setting the critical line between the two images. The best models are remarkably oriented in the G1-G2 direction with an ellipticity of about 0.12, but require a too high velocity dispersion (> 1300 km s^{-1}), in contradiction with the observed shear field. Lower values do not allow the critical line to go between the double image of the quasar. Therefore, discarding unusual mass distributions with shallower slope at large distance and smaller velocity dispersion, we must reject the hypothesis of a single lens at $z = 0.28$. Moreover preliminary results from the NTT can might exclude S3 as a possible counter-image, since its spectrum does not show emission lines similar to those seen in Q2. Further data are needed to confirm this.

Some very faint blue galaxies are found close to G1 and G2, but we do not detect a strong shear centered on them which also suggests that G1 and G2 do not belong to a massive structure. So the lens could be a double screen system, with a cluster at large z producing most of the shear effect, added to a small group centered on G1 and G2. Another possibility is that the large angular separation of the QSO images would be mostly due to a distant cluster, whereas the nearby group would weakly shear the distant cluster members. Besides, deep B images show a very faint object between Q1A and Q1B which could act as a perturbation. Further HST observations have confirmed the "non" multiplicity of the quasar components (Kristian, private communication).

5. Discussion and conclusion

Our investigation of the shear in the "blank field" Q2345+007 is, as far as we know, the first detection of a weak gravitational shear ever done. It reveals the presence of a cluster-like structure almost coincident with the location of two bright galaxies.

This brings to mind the possibility, first raised by Narayan, Blandford, & Nityananda (1984), that Q2345+007 A and B are two images of the same QSO, split by a cluster. In this case there should be a third image within a few *arcmin.* from the center, possibly fainter than B $\sim$ 23. There is another QSO at $z = 2.653$, at $\sim$ 2' from the center. At the moment, we cannot exclude the possibility that it also should have extra images (if Q2345+007 is not a physical pair).

The center of the coherent shear field lies near two bright galaxies at $z = 0.25$. From its magnitude we conclude that if it is produced by a dark mass associated with these galaxies, this mass cannot split Q2345+007, and in that case Q2345+007 must be a physical pair. However, we see many faint blue galaxies near the center of the shear field, which may possibly belong to a cluster at larger redshift. Such a cluster should account both for the shear field and for the splitting Q2345+007.

From the analysis of the Q2345+007 field, we see that the measurement of the shear field can bring strong constraints on complex multiple lenses and disentangle between different hypotheses.

One interesting application can be the following. Correlations between positions of > 1 Jy radio sources and foreground galaxies were found by Fugmann(1990) and by Bartelmann and Schneider (1993a&b and references therein). Bartelmann & Schneider (1992) calculated that this correlation can be caused by large scale dark matter inhomogeneities correlated with with galaxies. In fact, Bartelmann and Schneider (1993a&b) found evidence that the typical angular sizes of these inhomogeneities can be $\sim 10'$. Direct measurements of the shear fields within a few arcminutes from the most luminous quasars should test their hypothesis.

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