The New Gravitational Lens Candidate Q 1208+1011 and the Importance of High Quality Data

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1. Introduction

The ESO Key Programme "Gravitational Lensing: Quasars and Radio Galaxies" has been described by Surdej et al., 1989. One of the aims of this programme consists in identifying multiply imaged sources within a large sample of highly luminous quasars (HLQs). Indeed, both the so-called magnification bias and the redshift dependence of the optical depth for lensing point towards apparently bright and very distant objects as the best gravitational lens candidates. For this purpose, we acquire CCD images of these objects (hopefully under good seeing conditions) and carefully inspect the recorded frames, in search for multiple components or galaxies superimposed on the quasar image.

This visual inspection is, however, only a first step: we have now begun a systematic analysis of these CCD images using more sophisticated image-processing techniques, including deconvolution and point-spread function (PSF) subtraction. Up to now, we have analysed a sample of 153 quasars for which R-band images had been obtained. Most of these data come from the direct CCD camera at the 2.2-m telescope, from EFOSC at the 3.6-m and from the direct camera which was mounted at the NTT during its test period. Some of the results have been presented in September 1991 by Magain et al. (1992a) while a more complete statistical evaluation of gravitational lensing effects on HLQ images is in preparation (Surdej at al. 1992b).

The histogram of the image full width at half maximum (FWHM) is illustrated in Figure 1 for the 153 objects considered. The sharp peak at 0.7 arcsec corresponds to observations carried out at the ESO NTT, observations which took place only when the seeing was very good. The observations obtained during our regular observing runs correspond to the broader peak around 1.2 arcsec. The average seeing FWHM amounts to 1.0 arcsec for the whole sample.

These 153 HLQs were systematically inspected visually, in search for possible nonstellar images (extension, fuzz, . . .) or for companions, either stellar or diffuse. In addition, the PSF was subtracted from the quasar image whenever possible. The residuals were then examined for a possible superposition of a galaxy or of a stellar image.

2. PSF Subtraction

The PSF was determined from stellar images in the field of the quasar. An analytic profile, in the form of a generalized Moffat (1969) function, was fitted to all stellar images simultaneously, then subtracted. The residuals were recentred and a mean was computed. The composite PSF (analytic function + mean residual) was then fitted to all the images (quasar and stars) and subtracted. The final residuals were examined, and it was decided whether the quasar had been fitted satisfactorily or if a significant residual remained, in which case it was classified as "interesting". We then tried to identify the nature of the residual, either diffuse or point-like. In particular, a fit of two PSFs was attempted to see if the object could be modelled as a double image.

In the course of this systematic analysis, we encountered a number of problems, which are described below.

2.1 Non-linearities

First, it was found that, on the frames obtained with the ESO CCD # 5 (RCA, 30 μm pixels), the shape of the PSF was a function of the image level, the core of the brighter stellar images appearing flatter than for the fainter ones. That CCD had been used for the earlier observations at the 2.2-m telescope (i.e.

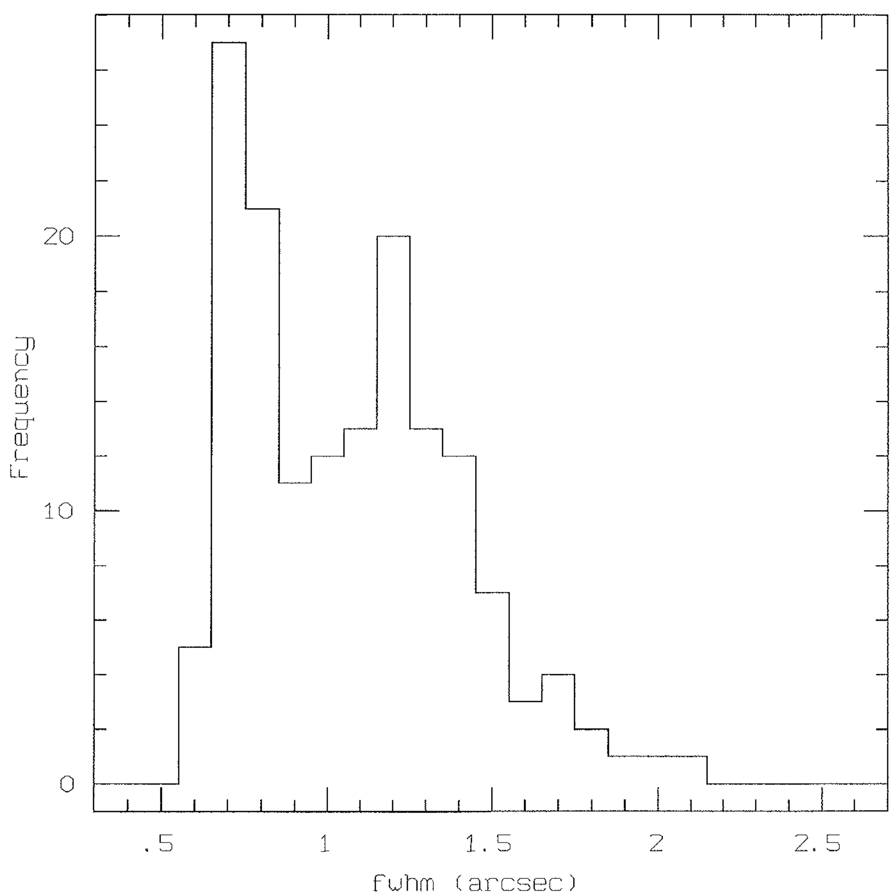

Figure 1: *Histogram of the image FWHM for the 153 quasars analysed.*

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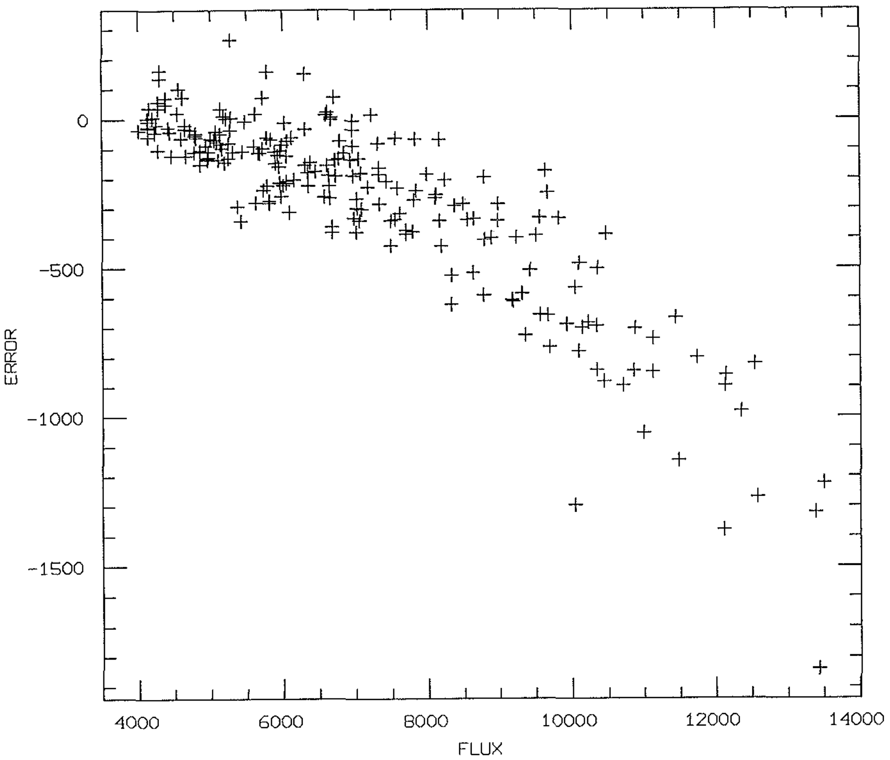

Figure 2: *Departure from linearity as a function of exposure level for the ESO CCD # 5. Both scales are in ADUs.*

from April 1987 to May 1988). We interpret this effect as caused by a non-linear response of the CCD, the recorded signal being non proportional to the amount of incident light. The amount of non-linearity could be estimated by self-calibration of the CCD images: the relation between light intensity and recorded signal was determined by requiring that the PSF shape be independent of the exposure level. That procedure was applied to all suitable images (that is, images containing several stars of various magnitudes) and the non-linearity curves derived from different frames were compared. This effect was found to be remarkably constant over the period covered by our data (4 runs, in April 1987, July 1987, November 1987 and May 1988). A mean curve was constructed and is presented in Figure 2. It shows a departure from linearity, having the form of a "saturation effect", reaching 10 % at the highest exposure levels. If not taken into account, this would introduce severe photometric errors and would make any PSF subtraction meaningless, except in those cases where the quasar and the comparison star are equally bright. We thus corrected the recorded signal, prior to PSF subtraction, by the relation:

$$S_{\mathrm{corr}} = \frac{S_{\mathrm{obs}}}{a + b\, S_{\mathrm{obs}}}$$

with a = 1.0382, b = −9.5565 10^{-6}. S_{obs} is the recorded signal (in ADU) and S_{corr} the signal corrected for the non-linearity. This relation is valid for signals above 4000 ADU. No correction was applied below that level.

2.2 Spatial variation of the PSF

A second problem encountered was the spatial variation of the PSF for the CCD frames obtained at the 3.6-m telescope with EFOSC, which is probably due to the rather complex optics of the instrument. This problem is illustrated in Figure 3, which was constructed in the following way. An exposure with a relatively good seeing (1.06 arcsec), and with rather isolated stars of suitable exposure level covering the whole field was selected. A mean PSF was constructed and subtracted from all stellar images used for its determination.

The residuals are shown in Figure 3 at their original position, but with a spatial scale which is expanded 6 times in order to improve their visibility. It is seen that these residuals (which should be negligible if the PSF shape was constant over the field) have a characteristic quadrupole shape, with an orientation depending on the position in the field. Indeed, if we draw straight lines originating from the centres of the stellar images and pointing in the direction of the residuals positive maxima, these lines would cross at approximately the same point, located somewhat to the left of the frame centre. This indicates that the stellar images are radially elongated, the centre of symmetry being slightly offset from the centre of the CCD image. The amplitude of these residuals amounts to 10 % of the peak intensity of the stellar image, which is an important effect.

Since the shape of the PSF depends on the position in the field, this means that, unless we are able to model that variation, the PSF can only be subtracted from those quasar images for which stellar images can be found very nearby in the field and, preferably, on both sides of the quasar so that an interpolation can be carried out quite accurately. As a consequence, only very few of the images obtained with that instrument were found suitable for PSF subtraction.

2.3 PSF variation with exposure level

The third problem was totally unexpected: we found that the sharpness of the stellar images varies with their intensity, in such a way that the *brighter* images appear *sharper*, the FWHM decreasing by an amount of the order of 5 % for a factor 10 in brightness. Moreover, it does not seem to affect the integrated signal, but just to redistribute the photons inside the stellar image, so that the photometry remains unaffected. This effect is present in data obtained with different instruments and different detectors, at different telescopes. However, its amplitude seems to depend on the configuration used. Unfortunately, our data do not allow to determine the origin of that effect: we suspect that it is due to the detector, but we cannot find any meaningful physical interpretation.

Figure 4 presents a plot of the PSF full width at half maximum (FWHM) for data obtained with the direct camera and ESO CCD # 11 at the 2.2-m telescope in April 1989.

In the absence of a physical explanation, we applied an empirical intensity-dependent correction to the PSF before subtracting it from the star and quasar images.

3. Results

The first and third problems encountered thus received an empirical correction, but, due to the number of parameters involved, the second one could not be modelled on the basis of the available data.

Given these problems, and given the facts (1) that some quasar images are not suitable for PSF subtraction because of a lack of comparison stars and (2) that the images obtained with the ESO NTT in the test period were not corrected for field rotation, we were left

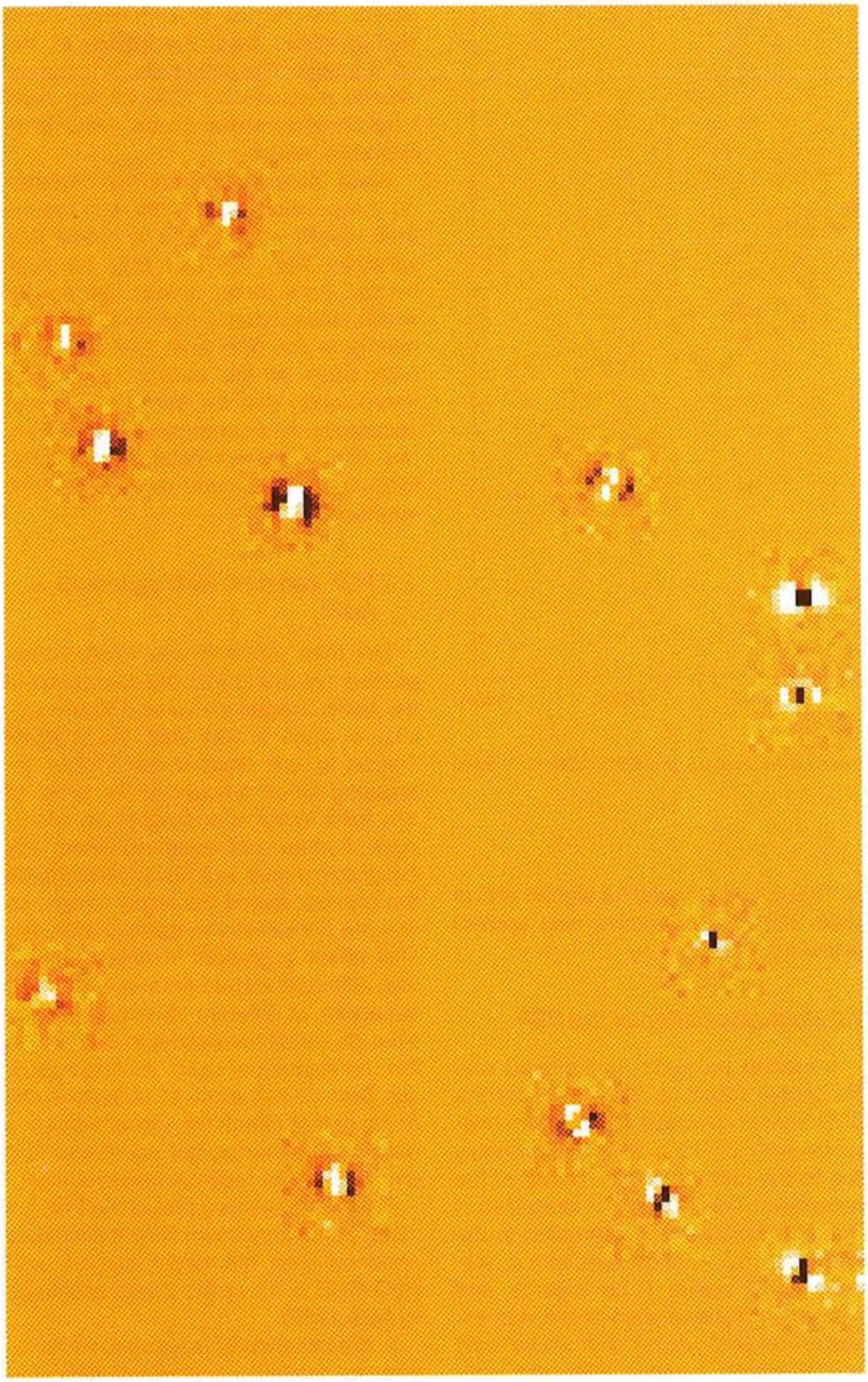

Figure 3: *Residuals of the PSF subtraction on an EFOSC image, showing the spatial variation of that instrument's PSF. See text for details.*

with 57 objects out of 153 for which the PSF could be satisfactorily subtracted.

The results concerning the superpositions of quasars with galaxies and the statistical frequency of lensing have been described by Magain et al. (1992a) and Surdej et al. (1992a). Here, we just wish to present the most spectacular result, which is the discovery of a new, rather extraordinary, gravitational lens candidate.

The quasar Q 1208+1011 was discovered by Hazard et al. (1986) and held for some time the world record with a redshift of 3.803. It is very luminous (M_v = –30.3) and, as such, was observed in April 1987 with the direct camera at the ESO/MPI 2.2-m telescope, the detector being a low-resolution RCA CCD (ESO # 5). We secured an R image, with an exposure time of 20 minutes. The seeing was rather poor (FWHM = 1.38 arcsec) and nothing special could be seen on the image. However, the PSF subtraction carried out in May 1991 revealed a very significant residual which could be interpreted as due to the presence of (at least) a second image.

Given these promising results, we decided to re-observe that object as soon as possible. New data could be obtained on July 7, 1991, with the direct camera at the 2.2-m telescope, equipped with a high resolution RCA CCD (ESO # 15). Two exposures were obtained, one with an R filter and the second with a B filter. The seeing was significantly better (0.9 arcsec for the R image) and the PSF subtraction confirmed the previous results. Two PSFs were then fitted to the R image of the quasar. The residual was then reduced to a negligible amount, showing that this object could be modelled by two point sources, separated by 0.45 arcsec and with a magnitude difference of 1.4 in the R band. Unfortunately, the B image is underexposed and no firm conclusion can be drawn from its analysis. Our first results were announced during the International Conference on Gravitational Lensing in Hamburg (Germany) on September 12, 1991 by Magain et al. (1992a). A more detailed account of that discovery may be found in Magain et al. (1992a).

In the meantime, we learned that Q 1208+1011 had been observed with the Hubble Space Telescope on July 22, 1991 in the framework of the snapshot survey (Bahcall et al., 1991). We obtained the image as soon as it became public, and were very pleased to see that it nicely confirms our results (Fig. 5).

In the absence of individual spectra of the two point sources, it is not possible to definitely conclude that Q 1208+1011 constitutes a new case of gravitational lensing. However, a good medium resolution spectrum of the whole system has been published by Steidel (1990). Interestingly enough, it shows strong absorption lines reaching nearly zero intensity. This allows to exclude the possibility that the fainter image corresponds to a foreground star. Indeed, the probability that such a star would have saturated absorption lines at precisely the same wavelengths as the high redshift quasar is essentially zero. Thus, we can conclude that Q 1208+1011 is either a binary quasar or a gravitational mirage. If the latter interpretation is the correct one, it implies that we have identified the multiply imaged quasar which is the most distant and with the smallest angular separation known up to date.

The fact that it could be detected on an image obtained in rather mediocre seeing conditions (1.38 arcsec) illustrates very clearly the power of adequate image analysis techniques. However, to be efficient, these techniques need to be applied to good quality data. This means: images obtained with a linear detector, with an instrument having a stable, well-defined PSF, and a good sampling (typically 0.1 arcsec per pixel). A sampling of 2 or 3 pixels per

FWHM would certainly not have allowed us to discover this very compact gravitational lens candidate.

Acknowledgements

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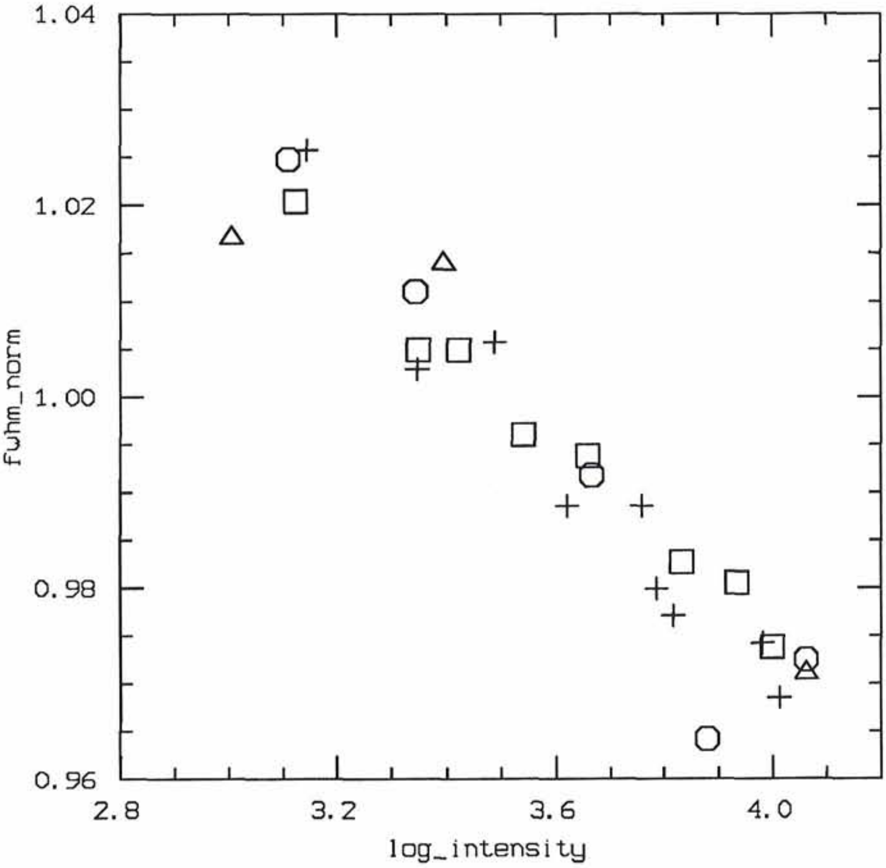

Figure 4: *The FWHM is plotted as a function of the logarithm of the central intensity for images obtained with ESO CCD # 11 at the 2.2-m telescope in April 1989. The FWHM is normalized to its value at log(intensity) = 3.5. Different symbols correspond to four different frames.*

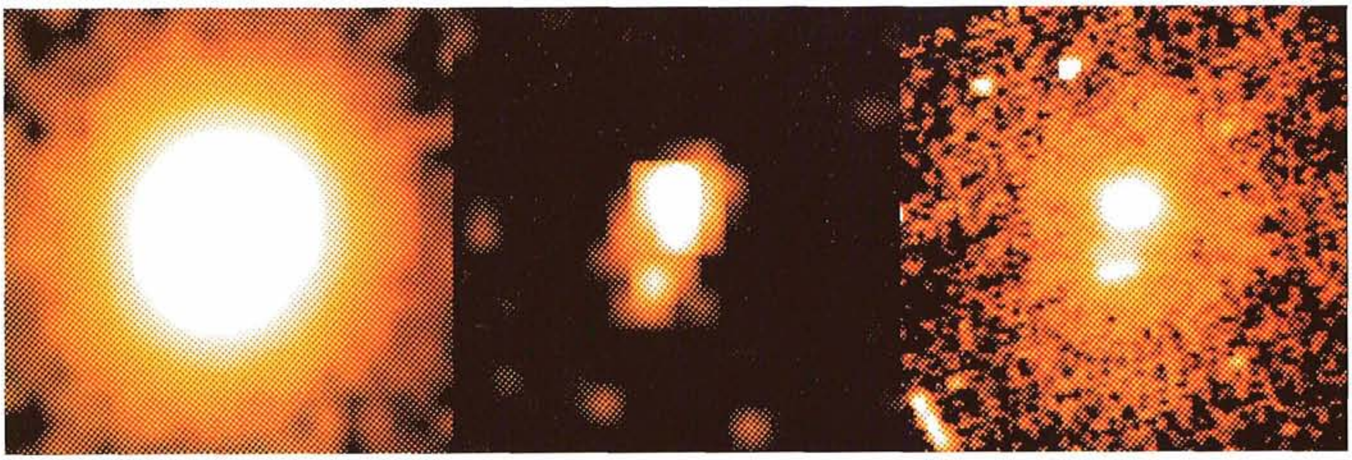

Figure 5: *Images of the highly luminous quasar Q 1208+1011. Left: ground-based image, seeing = 0.9 arcsec. Middle: deconvolution of the ground-based image using the algorithm described in Magain (1989). Right: HST image. These three images are re-sampled to the same scale and normalized to the same peak intensity. The intensity scale is logarithmic.*

Minor Planet Discovered at ESO is Named "Chile"

A minor planet which was first discovered on a photographic plate obtained with the ESO 1-metre Schmidt telescope in 1988 has now been named after the country in which the La Silla observatory is located.

The observation was made on February 13, 1988 by ESO night assistant Guido Pizarro, within the minor planet search programme by Belgian astronomer Eric W. Elst, who also found the new object on the plate. From a