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SEARCH FOR GRAVITATIONAL LENSING FROM A SURVEY OF HIGHLY LUMINOUS QUASARS*

J. SURDEJ**, J.-P. SWINGS
Institut d'Astrophysique, Université de Liège, Avenue de Cointe, 5, B-4200 Cointe-Ougrée, Belgium
P. MAGAIN
European Southern Observatory, Casilla 19001, Santiago 19, Chile
U. BORGEEST, R. KAYSER, S. REFSDAL
Hamburger Sternwarte, Gojenbergsweg 112, D-2050 Hamburg 80, Federal Republic of Germany
T.J.-L. COURVOISIER***
ST-ECF, European Southern Observatory, Karl-Schwarzschild-Str. 2, D-8046 Garching bei München, Federal Republic of Germany
K.I. KELLERMANN
National Radio Astronomy Observatory, Edgemont Road, Charlottesville, Virginia 22903-2475, USA
H. KÜHR
Max-Planck-Institut für Astronomie, Königstuhl, D-6900 Heidelberg 1, Federal Republic of Germany

* based on observations collected at the European Southern Observatory (La Silla, Chile) and at the National Radio Astronomy Observatory (Socorro, New Mexico)

** also, Chercheur Qualifié au Fonds National de la Recherche Scientifique (Belgium)

*** affiliated to the Astrophysics Division of the Space Science Department of ESA

ABSTRACT We recently initiated a high angular resolution direct imaging survey of a selected sample of Highly Luminous Quasars (hereafter, HLQs) : the observations are being carried out with the 2.2 m telescope at the European Southern Observatory (ESO, Chile) and with the Very Large Array (VLA) at the National Radio Astronomy Observatory (NRAO, New Mexico). The observing procedures are described in the present paper. Following the detection of several good candidates for gravitational lensing, we report here on preliminary results concerning the frequency of occurrence of resolved HLQ images. When more data will become available, this program should contribute to a better understanding of the effects of gravitational lensing on the observed quasar luminosity function, on the source counts of extragalactic objects and, possibly, on the QSO phenomenon itself.

1. INTRODUCTION

The first case of a gravitationally lensed distant object has been identified by Walsh et al. (1979) almost sixty years after the first observational evidence of light bending by the Sun (in 1919). There are presently up to eight additional candidates of multiply imaged distant quasars (Weymann et al. 1980; Weedman et al. 1982; Lawrence et al. 1984; Djorgovski and Spinrad 1983; Huchra et al. 1985; Hewitt et al. 1985, 1987; Surdej et al. 1987). However, no lensing object has yet been identified for approximately half of the proposed cases ! In addition, gravitational lensing by an intervening object has recently been suggested for the giant radio galaxy 3C324 (Le Fèvre et al. 1987), as well as for an extragalactic arc near the galaxy cluster Abell 370 (Soucail et al. 1987).

For the particular case of Q0957+561 A and B, a very convincing physical model has been proposed by Young et al. (1980, 1981) : the observed images are produced through the gravitational lensing of a single distant quasar (z_q = 1.41) by a giant elliptical galaxy and its associated cluster (z_L = 0.36). Using the difference in light travel time between the individual images of Q0957+561, Borgeest and Refsdal (1984) and Falco et al. (1985) have derived an upper limit on H_o. It is clear that a statistical evaluation of the occurrence of gravitational lensing within a well-defined sample of quasars is of prime importance to better understand the QSO luminosity function and possibly the QSO phenomenon itself (cf. Barnothy and Barnothy, 1968), to test cosmological models (Refsdal, 1964, 1966) and to probe the luminous and dark matter distribution on various scales in the Universe (see Canizares, 1981).

The answer to the question "What fraction of QSOs are multiple due to gravitational lensing ?" is very closely related to that to the question "What is the mass distribution at different scales in the Universe ?". If we consider for instance scales typical of galaxies and clusters, we know that the answer to the first question is highly dependent on the central velocity dispersions adopted for the bright elliptical galaxies and on the maximum surface densities in large galaxy clusters (Turner et al. 1984). More generally, any prediction made for the expected number of multiply lensed quasars is very much dependent on the adopted model (Barnothy and Barnothy 1968; Tyson 1981; Peacock 1982; Turner et al. 1984; Hinshaw and Krauss 1987). Once more, we naturally conclude that an observational approach is required to further constrain our understanding of gravitational lensing.

Adopting such a viewpoint, we have recently initiated a systematic search for new gravitational lenses. In the following, we consider that the apparently ($m_V \lesssim 18.5$) and intrinsically ($M \lesssim -29.0$) luminous quasars constitute very promising candidates to search for the presence of gravitationally lensed images at arcsec and sub-arcsec angular scales. Indeed :

i) the HLQs form a particularly high flux limited sample of QSOs for which the probability of detecting multiply lensed images is higher than for a volume limited one (Turner et al. 1984).

ii) The HLQs are the most likely objects for which we may assume that their intrinsic brightness is partially due to gravitational lensing.

iii) The large cosmological distances suggested by the higher redshift values observed for the HLQs imply a high probability for gravitational lenses to be located along their line-of-sights. This is also suggested by the presence of rich absorption systems at redshifts $z_a < z_q$ recorded in the optical spectrum of most HLQs.

iv) We suspect that the paucity of known multiply lensed QSO images with angular separations in the range $\lesssim 2 - 3$ arcsec is mainly caused by observational biases. High resolution imaging of the HLQs with the Hubble Space Telescope, the Very Large Array and ground based optical telescopes under very good seeing conditions ought to bring important clues on the occurrence of lensing effects by galaxies or any other class of unknown massive objects.

A first observing run with the ESO/MPI 2.2 m telescope in November 1986 has led to the discovery of UM673 as a new case of gravitational lensing (Surdej et al. 1987, 1988). This system consists of two lensed QSO images A(m_R = 16.9) and B(m_R = 19.1), separated by 2.2 arcsec at a redshift z_q = 2.719. The lensing galaxy ($m_R \simeq 19$, z_L = 0.493) has also been identified. It lies very near the line connecting the two QSO images, and is about 0.8 arcsec away from the fainter one. Application of gravitational optometry to this system leads to a value $M_0 \simeq 2.4\ 10^{11}\ M_\odot$ for the mass of the lensing galaxy and to $\Delta t \simeq 7$ weeks for the most likely travel-time difference between the two light paths from the QSO (assuming H_0 = 75 km $sec^{-1}\ Mpc^{-1}$, q_0 = 0). CCD photometric monitoring of UM673 A and B has begun in October 1987 using the Danish 1.5 m telescope

(ESO, La Silla) in order to determine the time delay between the two QSO images.

The techniques used for searching multiply lensed quasars among the HLQs are described in Section 2. Preliminary results on the observed frequency of resolved HLQ images are given in Section 3. The conclusions are presented in the last Section.

2. DESCRIPTION OF OUR OBSERVATIONAL SEARCHES FOR GRAVITATIONAL LENSING

Although our present collaborative search for gravitational lensing was initially set up because of the unique observing capabilities that should be offered by the Space Telescope (exceptional angular resolution, very good dynamic range, etc.), the delay in obtaining access to ST has prompted us to attempt the direct imaging of HLQs from the ground. We describe hereafter the observing techniques followed in our optical and radio searches.

2.1. Ground based optical search

During a total of 18 nights already allocated to our program at the European Southern Observatory, a CCD camera (RCA SID 501 EX chip, 320 x 512 pixels of 30 μm) was used at the Cassegrain focus of the ESO/MPI 2.2 m telescope in order to perform, at high angular resolution, direct imaging of HLQs $m_V \lesssim 18.5$, $M \lesssim -29.0$, Decl. $\lesssim + 20°$). These were selected from the Véron and Véron (1987)'s catalogue of quasars. Under average seeing conditions near FWHM = 1.2 arcsec, we succeeded in observing a total of 111 HLQs through wide- (B, V, R or I), and whenever possible, narrow- band filters chosen to isolate one of their bright redshifted emission lines (Lyα or occasionally CIII]) as well as a nearby portion of their continuum. Whereas a detailed analysis of all recorded CCD frames will provide in the near future information on the dynamic range achieved on each target and on the relevance of lensing effects (Courvoisier et al. 1988), the straight comparison of two such different color CCD frames gives an efficient means of selecting QSOs and/or QSO images with similar redshifts (cf. Djorgovski et al. 1985). Spectroscopic identification of the resolved HLQs becomes necessary at this stage. Until now, only one of the resolved objects has been thoroughly studied spectroscopically; i.e. UM673 (see Surdej et al. 1987, 1988). More information on the other resolved HLQs will be given in Section 3.

2.2. VLA search

A radio detection survey of 19 optically selected HLQs (Decl. > -40°) has first been carried out with the VLA (C/D configuration, 6 cm) in January 1987. Among these observed HLQs, only four have been found to be sufficiently bright sources in order to be mapped with the VLA at higher angular resolution. Observations of these were made with the VLA (A configuration, 6 cm, angular resolution ≃ 0.5 arcsec) in October 1987. Two of the four sources are resolved, one is unresolved and the fourth one has insufficient dynamic range to conclude; we also point out that we did not succeed yet in optically resolving the two detected multiple radio sources ($\Delta\Theta \simeq 1$ and 1.4 arcsec).
Furthermore, three of our optically resolved HLQs, known to be observable at radio wavelenghts, were also mapped with the VLA in October 1987. Two of these are resolved at 6 cm. Finally, we failed to detect the gravitational lens system UM673 A and B at 3.6 (resolution ≃ 0.4 arcsec) and 6 cm during 30 minute observations with the VLA in the A configuration.

3. PRELIMINARY RESULTS ON THE OPTICAL OBSERVATIONS

In order to delineate as clearly as possible the observational characteristics of the quasars under study, we have drawn in Figures 1-3 histograms representing the redshift (Fig. 1), the apparent visual magnitude (Fig. 2) and the absolute magnitude (Fig. 3) of the 111 HLQs imaged with the ESO/MPI 2.2 m telescope (cf. Section 2.1.). The histogram in Figure 4 shows the distribution of the seeing conditions (FWHM) characterizing the best CCD frames that were obtained for each object.

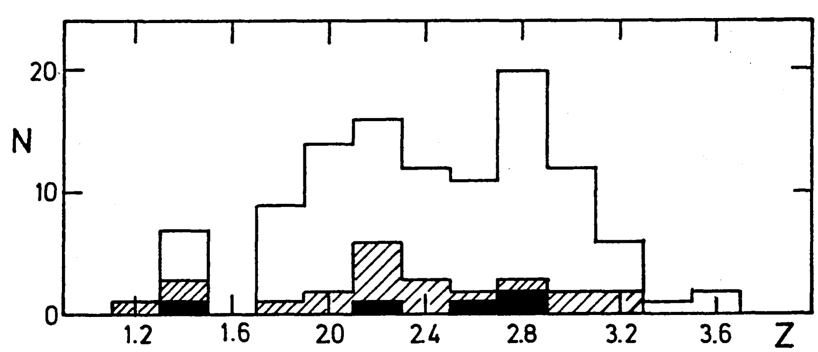

Fig. 1 Histogram representing the redshift of the 111 optically selected HLQs from the Véron and Véron (1987)'s catalogue of quasars. The dashed and dark areas refer to a sample of 25 interesting HLQs and to that of 5 very good candidates for gravitational lensing, respectively, as described in the text.

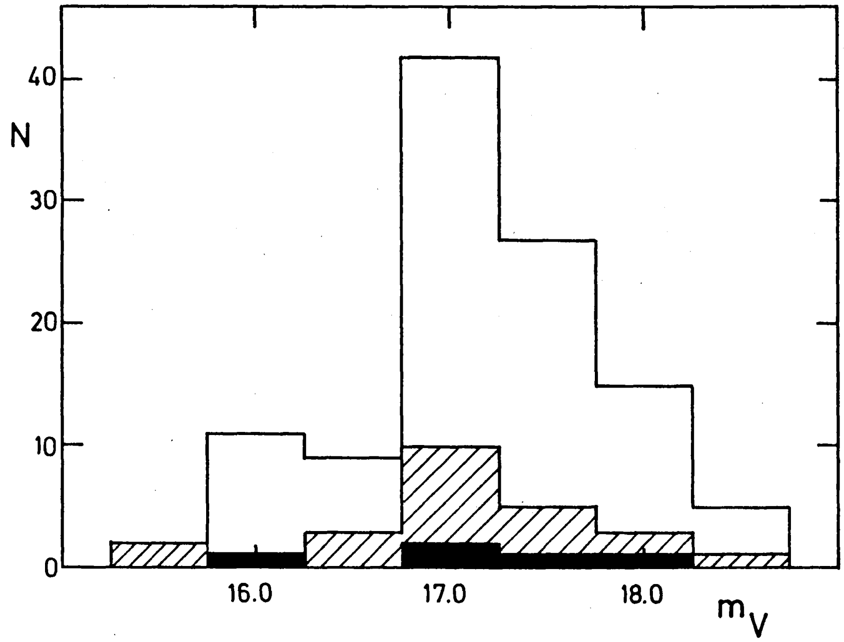

Fig. 2 This histogram refers to the apparent visual magnitude of the 111 optically selected HLQs (see caption in Fig. 1 for additional information).

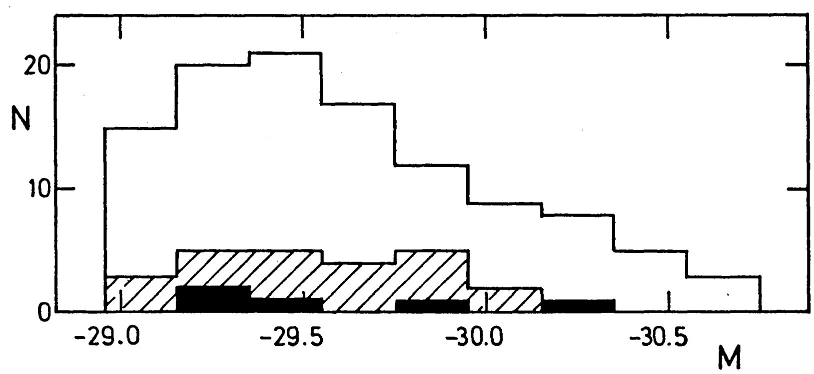

Fig. 3 This histogram refers to the absolute magnitude (H_o = 50 km sec^{-1} Mpc^{-1}, q_o = 0, $\bar{\alpha}$ = 0.7) of 110 HLQs. One HLQ with M = -31.6 has not been included (see caption in Fig. 1 for additional information).

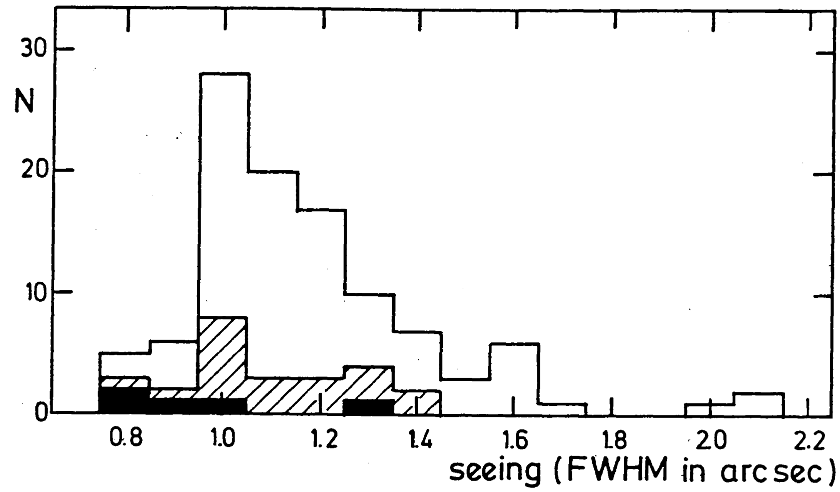

Fig. 4 Histogram representing the distribution of the seeing disk (FWHM in arcsec) for 106 (out of 111) of the HLQs that were imaged with the ESO/MPI 2.2 m telescope (see Text). Data are temporarily missing for 5 HLQs.

Twenty-five of these 111 luminous quasars were found to be interesting because of one of the following reasons :

- multiple images,
- elongated image,
- presence of a jet-like feature,
- presence of a faint nearby galaxy,
- the image shows some fuzz,
- etc.

The dashed region of the histograms in Figures 1-4 refers to these 25 interesting HLQs. Furthermore, five of these 25 objects turn out to be exceptionally good candidates for gravitational lensing (cf. the several examples shown at the conference). These are represented in Figures 1-4 by the dark area of the histograms. It is interesting to note from Figure 4 that four of the five best potential candidates for gravitational lensing have been identified on CCD frames taken under optimal seeing conditions (i.e. FWHM $\lesssim$ 1 arcsec). It is clear that observational biases play a major role in the detection of gravitational lens effects. An illustration of these is given in Figures 5 and 6. Figure 5a represents radial intensity profiles, along one same direction, of the image of a selected HLQ that has been observed with a CCD behind a Bessel B filter under various seeing conditions (FWHM = 1.5 and 1.0 arcsec).

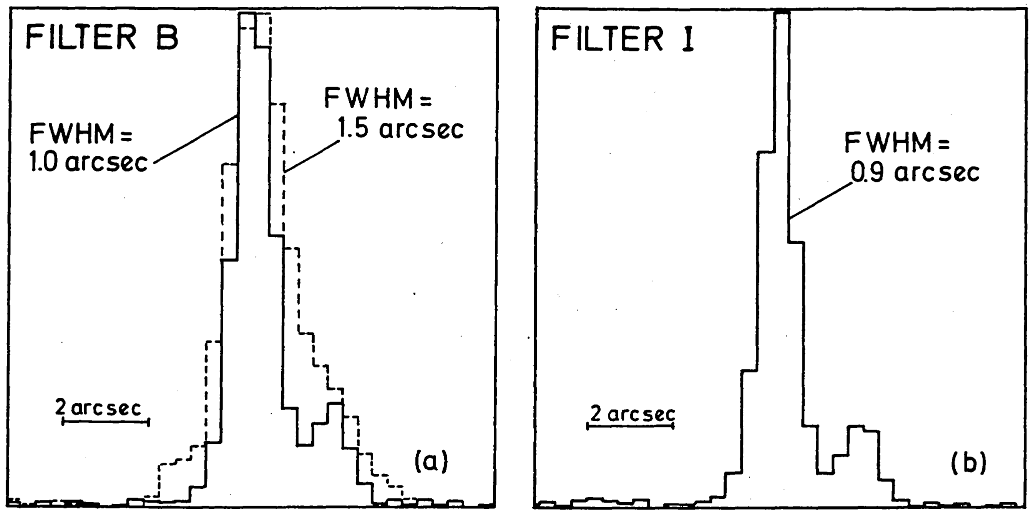

Fig. 5 (a) Radial intensity profiles, along one same direction, of the image of a good lensed HLQ candidate observed with a CCD camera behind a Bessel B filter when the seeing disk was 1.5 and 1.0 arcsec.
(b) As (a) but for an I filter and a seeing disk of 0.9 arcsec.

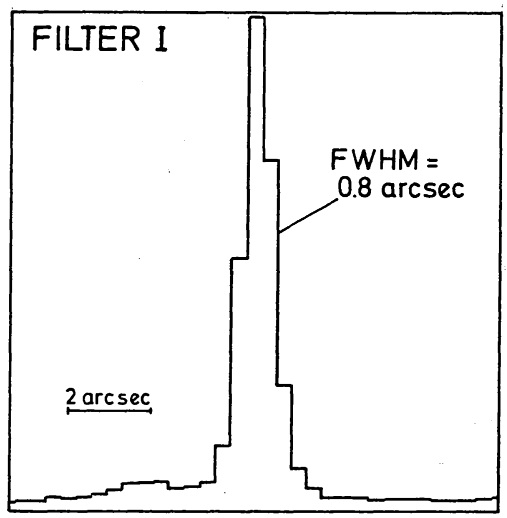

Fig. 6 Radial intensity profile of the image of another good lensed HLQ candidate observed with a high S/N ratio under a seeing of 0.8 arcsec. Note the presence of a very faint secondary image to the left.

This example clearly indicates that the lensed HLQ candidate, appearing barely elongated on the 1.5 arcsec exposure, would have been missed under (slightly) less favourable seeing conditions. Figure 5b was similarly constructed from a CCD frame taken through a I filter and under a seeing (FWHM) ≃ 0.9 arcsec. A more general analysis of the B [, V, R] and I CCD frames available for this HLQ confirms that it is a very good candidate for gravitational lensing. The separation between the two unequally bright, although resolved, images is about 2 arcsec. Figure 6 shows, for the case of another good lensed HLQ candidate, the importance of getting a sufficiently high S/N ratio in order to detect the presence of faint secondary images.

4. CONCLUSIONS

We have shown in this paper that our search for gravitational lensing from a survey of optically selected HLQs appears very promising. Indeed, observational features (multiple images, image elongation, jet-like feature, fuzz, etc.) possibly associated with the HLQ phenomenon have been detected for more than 20 % of the objects under study. While it is not yet known how many of the HLQs are gravitational mirages, at least 5 (out of 111) of the investigated quasars appear to be highly luminous because of amplification of their brightness by gravitational lensing. Since "amplification" does not necessarily mean "multiplicity of images", it could very well be that many more HLQs (and possibly quasars) are gravitationally lensed (cf. Barnothy and Barnothy, 1968). Whereas it is clear that observational biases conspire against the detection of many gravitational lens systems at arcsec and sub-arcsec angular scales, it is likely that the nicest cases ($\Delta\Theta \gtrsim 2$ arcsec) yet to be found will rely more ... on the generosity of the future observing program committees.

Acknowledgments

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DISCUSSION

Veron :

What was the estimated amplification factor for the UM object?

Surdej : There is a very recent calculation that shows it could be as high as a factor of several hundred, although that seems almost unbelievable. We had been working with calculations that indicated an amplification factor of a factor of several, less than 10.

MacAlpine : I'm wondering what one should be looking for on Schmidt plates that would lead to finding some of these things. Is there anything else that drew your attention to UM673?

Surdej : No. We just worked from the luminosity of the sources.

Osmer : It seems to me you're doing just the right thing: using a CCD detector, which has a better dynamic range than plates, at a better scale than is used for Schmidt surveys. Consequently, you find these fascinating results.

Turner : I would just mention the well known result that the number of known lenses with separations of a few arc seconds implies that there should be a large number with separations of 1" or less.