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ESO Key Programme "Gravitational Lensing: Quasars and Radio Galaxies": a Status Report

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Abstract

The scientific background and objectives of our ESO Key Programme are first recalled. A brief account of our research activities (observing runs at ESO and elsewhere, meetings, etc.) is then given. Preliminary scientific results are presented concerning 1) our observational database for highly luminous quasars and distant powerful radiogalaxies; 2) speckle observations of highly luminous quasars; 3) the photometric monitoring and 4) detailed studies of several known gravitational lenses; 5) optical observations of 3C and 4C radio galaxies and 6) of the well known Einstein ring MG 1131+0456.

1. Scientific background and objectives

In October 1988, when our team applied for observing time at ESO in the framework of a Key Programme (Surdej *et al.* 1989), it was clear that most of the known gravitational lenses were associated with either highly luminous quasars (HLQs, typically $M_V < -28$; cf. the cases of Q0957+561, Walsh *et al.* 1979; PG 1115+080, Weymann *et al.* 1980; Q2237+030, Huchra *et al.* 1985; UM673, Surdej *et al.* 1987; H1413+117, Magain *et al.* 1988; UM425, Meylan & Djorgovski 1988) or distant powerful radio sources [DPRSs, $z > 1$ and $P(178\mathrm{MHz}) > 10^{28}\,\mathrm{W\,Hz^{-1}}$; see *e.g.*, 3C324, Le Fèvre *et al.* 1987].

We therefore proposed to carry out at ESO a search for gravitational lensing effects within a sample of HLQs and DPRSs. Further arguments motivating such a programme were that: 1) both the HLQs and DPRSs are taken from high flux limited samples of extragalactic objects for which the probability of detecting lensing effects is higher than in volume limited ones (Surdej *et al.* 1988a; Hammer & Nottale, 1986); 2) the HLQs and DPRSs are the most likely objects for which we may assume that their intrinsic brightness is partially due to amplification by gravitational lensing (Surdej *et al.* 1988b; Hammer *et al.* 1986); 3) the large cosmological distances suggested by the higher redshift values observed for both the HLQs and DPRSs imply a high probability for gravitational lenses to be located along their lines-of-sight (this is also suggested by the rich absorption systems at redshifts $z_a < z_q$ recorded in the optical spectrum of most HLQs); 4) we suspected that the paucity of known cases of multiply lensed HLQ and DPRS images with angular separations in the range $\theta < 2 - 3''$ was caused by strong observational selection effects (Surdej *et al.* 1988b).

Since May 1989, whenever the seeing conditions are optimal on La Silla (*i.e.*, FWHM $< 1.2''$), we are using regularly the Danish 1.5m (direct CCD camera), the ESO/MPI 2.2m (direct CCD camera, speckle camera, EFOSC2), the ESO 3.6m (EFOSC1) and the NTT (EFOSC2 and EMMI) telescopes to search for gravitational lensing effects among HLQs and DPRSs. Not only are we trying to detect multiply lensed HLQ and DPRS images with typical angular separations smaller than 1", but we are also looking for the presence of an excess of foreground objects in the vicinity of the relevant targets or even for possible signs of a lensing galaxy whose image would be superimposed over that of the objects under study.

Our ESO Key Programme is intended to lead to a better understanding of the source counts, luminosity function and cosmic evolution of quasars and distant radio sources. It should also contribute to an independent determination of the Hubble parameter H_0 (Refsdal 1964, 1966; Borgeest & Refsdal 1984), and to that of galaxy masses (Borgeest 1986) on account of the expected time delay between the brightness variations of multiply lensed QSO images. The modelling of known and new cases of gravitational lens systems should also provide valuable information on the distribution(s) of luminous and dark matter at various scales in the Universe. Finally, information on the size and structure of quasars should be derived from the photometric monitoring of micro-lensing effects in very compact groups of multiply lensed QSO images such as Q2237+030, H1413+117, etc. (see Grieger *et al.* 1986, 1988).

2. Research activities

2.1 Observations at ESO

In our initial ESO Key Programme application, we requested a total number of 129 nights of observing time with the Danish 1.5m (10 nights), ESO/MPI 2.2m (55 nights) and ESO 3.6m or NTT (64 nights) telescopes, to be distributed over a period of 3 years. Our ESO Key Programme "Gravitational Lensing: Quasars and Radio Galaxies" has finally received 111 nights, and the first observing run took place in May 1989. Within exactly a period of two years, 55.5 nights (instead of 74 nights) have been allotted to our programme in the form of 14 independent observing runs (16 different observers) and 41 periods of 90 min. for the photometric monitoring of known gravitational lens systems (two of our observers being in fact resident on La Silla). It should be noted that the non permanent availability of a direct CCD camera at the focus of the ESO telescopes has precluded the possibility of scheduling such observations every week, as planned initially. We would like now to point out that of the 55.5 nights allocated to our programme, 8% of the total observing time has been lost due to technical problems. During 23% of the remaining time, no observation could be made because of bad weather conditions. Finally, the seeing conditions have turned out to be worse than $1.2''$ during 40% of the remaining nights. In conclusion, only 24 effective clear nights (*i.e.*, 43% of the already allocated time), with seeing conditions better than $1.2''$, turned out to be useful for us to achieve successfully the scientific goals exposed in our programme.

2.2 Observations at other institutions

Also in the context of further studies of gravitational lens systems, most of the members of our present team are regularly applying for observing time at other institutions (Calar Alto, CFHT, CTIO, HST, MMTO, NOT, NRAO-VLA, OHP, Pic-du-Midi, etc.). This allows us to have access to northern sky objects, to complementary instrumentation (cf. integral field spectroscopy with SILFID, high resolution imagery and/or spectroscopy in the UV, etc.) and also different spectral ranges (radio, far-UV). Several studies of gravitational lenses based on sets of data obtained at ESO and at other observatories are presented in Section 3.

2.3 Meetings

Since image reduction facilities are available in ten (of the eleven) institutes participating to the ESO Key Programme (ESO KP), there is no surprise that, in practice, the acquisition, reduction and interpretation of the observational data are entirely worked out by existing sub-groups of members of the present collaboration (cf. list of references). Informal meetings are frequent between members of these sub-groups. In addition to these, general meetings between all members of the ESO KP group are organised approximately every six months. Some of these coincide with international workshops (cf. the Toulouse Workshop on Gravitational Lensing held in September 1989) or conferences (our next meeting will take place during the conference on Gravitational Lenses organized in Hamburg on 9–12 September 1991). There are already plans to devote the 1993 Liège International Astrophysical Colloquium to the general topic of “Gravitational Lensing”.

2.4 General bibliography

One of us (PV) has compiled and keeps updated a general bibliography on the subject of gravitational lenses. This extensive bibliography does actually include about 500 articles published between 1936 and 1991. For those interested, this work is available upon simple request to Dr. P. Véron, Observatoire de Haute Provence, F-04870 Saint-Michel l’Observatoire, France.

3. Preliminary scientific results

3.1 Observational databases

A natural product of our ESO Key Project has been to set up two databases containing observational information for approximately 200 HLQs (Liège database) and 30 DPRSs (Meudon database). As far as the observed HLQs are concerned, we shall soon report on countings of galaxies in the fields of these objects (Van Drom *et al.* 1991). Preliminary results based on the counting of galaxies from a sample of NTT CCD frames are as follows. The counting of galaxies near (and in a comparison field close to) some 91 HLQs has been recently achieved: the result essentially confirms the claim by Magain *et al.* (1990) that there is an excess of galaxies, of the order of 50%, near the position of the HLQs (within a radius of about $15''$, see Fig. 1). Combining both the recent NTT and the Liège/Hamburg/ESO samples of quasars (observed in the R band) we intend to report soon about these interesting results, as well as on statistics concerning the image multiplicity (no new case was found in the NTT data) and several interesting cases of superimposed galaxies.

In our search for multiply lensed HLQ images, spurious candidates corresponding to random projections between QSOs and field stars, etc. have of course been identified. A first list of such undesirable associations of objects has been published by Véron *et al.* (1990).

3.2 Speckle observations

The status of the data reduction of the speckle images collected for the HLQs in December 1989 is summarized below. The digitization and first speckle masking of the 15000 speckle images obtained for the gravitational lens system UM673 (Surdej *et al.* 1987) has in fact just been completed at the MPI für Radioastronomie in Bonn.

Both the gravitationally lensed UM673 A and B images are very well detected and separated ($2.2''$). An additional faint structure, present in different image sub-samples, is also detected with a good confidence level at an angular distance from the A component of approximately $0.2''$. Applying an improved photon bias

Figure 1. Normalized counts of galaxies in 3 concentric rings around HLQs from the recent NTT (stars) and the Liège/Hamburg/ESO (circles) samples of quasars (91 and 83 HLQs, respectively) observed in the R band. 1σ error bars are indicated.

compensation technique and a new method for evaluating the complete bi-spectrum (up to now only a subset of the bi-spectrum was used) will allow soon to enhance further the signal to noise ratio of this new faint image. Although the possible multiplicity of the A image had been predicted earlier (Surdej *et al.* 1988a), the present observations will help us in setting very important constraints on the mass distribution in the lensing galaxy, on the time delays as well as on the true position of UM673 in the source plane. Evaluation of the remaining 10^5 speckle images for two other HLQs and the Einstein Cross Q2237+030 will run now much faster since the reduction hardware and restoration technique have been set up. Good evidence has been found for the discovery of triple images, with separations of the order of $0.15''$, for one of the two HLQs under study.

3.3 Photometric monitoring of several known gravitational lens systems

Photometric monitoring of multiply lensed quasars is important for at least two reasons:

(1) Refsdal (1964, 1966) has first pointed out that the difference in light travel time between two images of a gravitationally lensed quasar is inversely proportional to the Hubble parameter H_0 . Because many quasars are known to be variable,

the difference Δt can be found simply by cross correlating the light curves of multiple images. Application of this technique to several gravitational lens systems is bound to result in a consistent and independent determination of H_0 (Vanderriest *et al.* 1989). Furthermore, the mass of the deflecting galaxy may be determined irrespective of the value of H_0 (Borgeest 1986);

(2) Variability of a lensed QSO image may also arise from micro-lensing effects. Of particular interest are the large amplification events which may occur when a compact source crosses a critical lightcurve (see Chang & Refsdal 1979, 1984; Paczyński 1986).

We shall report soon on the reduction and analysis of the lightcurves for the A, B, C and D images of the Einstein Cross (Q2237+030) observed at ESO (Remy *et al.* 1991). This study is a very interesting by-product of our photometric monitoring of known gravitational lens systems. Preliminary lightcurves for the A, C and D components relative to B are shown in Figure 2. The photometric calibration of the zero-points should be ready shortly. Important results concerning the existence of micro-lensing effects for components A, C and/or D can readily be seen in Figure 2. Our next goal will be to reduce the CCD frames obtained for the other known gravitational lens systems H1413+117, UM673 and UM425. A great wealth of direct imagery has been obtained for these objects in the context of our ESO KP photometric monitoring.

3.4 Probing the size of Ly-α clouds

Smette *et al.* (1990, 1991) have presented a study of the Ly-α forest on the basis of high resolution spectra obtained at MMTO, ESO and CTIO for the A and B images of the gravitationally lensed high-redshift quasar UM673 (Surdej *et al.* 1987, 1988a). They find in their 2 Å resolution spectra that all the absorption lines detected at a 5σ level in the spectrum of the fainter B image are present in the A image; however, 2 anti-coincidences are reported, *i.e.*, 2 lines detected in the spectrum of A which do not have their counterpart in that of B at more than a 3σ confidence level. Given the additional fact that corresponding Ly-α lines in the spectra of A and B have their equivalent widths well correlated, this proves that both light beams actually cross the same clouds. Most of the velocity differences between corresponding lines are compatible with $0\,\mathrm{km\,s^{-1}}$ within the error bars (with a standard deviation of $17\,\mathrm{km\,s^{-1}}$). By means of Monte-Carlo simulations, Smette *et al.* have derived a best value of $12\,h_{50}^{-1}$ kpc ($H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $q_0 = 0$) for the 2σ lower limit and of $160\,h_{50}^{-1}$ kpc for the 2σ upper limit of the diameter of spherical Ly-α clouds. However, if the two anti-coincidences are interpreted as due to an MgII doublet at $z = 0.4261$, they find in this case a best value of $23\,h_{50}^{-1}$ kpc to the 2σ lower limit of the Ly-α cloud diameter, but no upper limit any longer. Smette *et al.* suggest how to make use of the present results and those reported for the number of Ly-α anti-coincidences in the spectra of Q2345+007 A and B (Foltz *et al.* 1984) in order to assess the physical nature (binary quasar or dark gravitational lens) of the latter

Figure 2. Relative light curves for the A,C and D components of the Einstein Cross (Q2237+0305) with respect to the B component.

system.

3.5 The Clover Leaf H1413+117

Following the discovery at ESO of the quadruply lensed quasar H1413+117, also known as the Clover Leaf (Magain *et al.* 1988), Angonin *et al.* (1990a,b) have obtained, under optimal seeing conditions (FWHM $\simeq 0.6''$), new data for this system using the bidimensional spectrograph SILFID at the Cassegrain focus of the CFH telescope. The spectra recorded for each of the four individual images turn out to be quite similar, except for the narrow absorption line systems (probably related to the lenses) seen in images A and B, and for marked differences in the spectrum of image D (see Fig. 3). When compared to the other three images, the spectrum of D shows smaller values for the emission lines/continuum ratio and a larger equivalent width for absorption features located in the blueshifted P Cygni profiles of SiIV and CIV. Possible explanations of these observations are discussed in terms of micro-lensing (see also Kayser *et al.* 1990) and/or intrinsic variability of the source.

3.6 3C and 4C galaxies

New NTT discoveries on distant radio galaxies and gravitational lensing have been recently reported by Hammer & Le Fèvre (1991). These include: 1) the spectroscopic discovery of foreground galaxies close to the line-of-sight to 3CR 255, 2) a new gravitational lens candidate for the multiply lensed radio source 3CR 297 and 3) the spectroscopic identification of a galactic M-type star as the brightest and central component of the high-z galaxy 3CR 368. A detailed analysis of all these data is to be reported elsewhere.

Figure 3. Spectra of the 4 images of the Clover Leaf as observed with SILFID at the CFH telescope. Note the difference in the structure of the BAL troughs for image D (arrows).

3.7 MG1131+0456

This radio source has been discovered by Hewitt *et al.* (1988) in the framework of a large radio survey with the VLA. Its radio morphology consists of an almost complete ring accompanied by a pair of compact sources nearly diametrically opposed. As Kochanek *et al.* (1989) have shown, these observations may be simply interpreted as due to the gravitational lensing effects of a foreground massive galaxy onto a distant background radio core plus its associated jet. Hammer *et al.* (1991) report on the possible optical detection with the NTT of the Einstein ring associated with this unique system and on spectroscopic data obtained for this interesting gravitational lens system.

4. Future prospects

We believe that the numerous preliminary scientific results obtained during the first half part of this ESO Key Programme already clearly emphasize the real importance of gravitational lensing effects on our understanding of the distant Universe.

During the second part of this project, we shall of course continue the detailed physical studies (cf. photometric monitoring) of the various known gravitational lenses, but we shall also spend more time on the speckle observations of HLQs, optical imagery and spectroscopy of 3C and 4C radio sources, as well as on obtaining deep direct R CCD frames for a complete sample of approximately 40 HLQs, which are also known to be radio loud.

In collaboration with B. Pirenne (ST-ECF), we are regularly visualizing the frames of HLQs obtained with the Planetary Camera within the HST Snapshot Survey and we are also presently inspecting extracted images from the Palomar "Quick V" and "UK SERC J" surveys for approximately 1500 quasars in order to identify potential gravitational lens candidates with large image separations ($\theta > 3''$). We intend to carry out high resolution imaging of all candidates which will turn out to be interesting and also of bright quasars which are identified spectroscopically in the framework of another on-going ESO Key Programme (Reimers 1990).

Exchange of direct CCD frames of quasars is also foreseen with the members (J. Bergeron and P. Boissé) of another ESO Key Programme.

Let us finally mention that seven young members of our group are preparing Ph.D. theses based, at least partially, upon observations collected in the framework of this ESO Key Programme.

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DISCUSSION

Boissé: My question concerns the quasar with two galaxies S-E for which you found a third one just superimposed onto the quasar. Is it clear that the remaining object after subtraction is 1) significant, (*i.e.*, much stronger than the residuals you get when subtracting the PSF to stars in the field, and 2) extended?

Surdej: We performed all possible kinds of checks that we could think of (subtraction of the PSF from other comparison stars on the same CCD frame, etc.) Our detection of a bright galaxy superimposed over the QSO image is very secure.