GRAVITATIONAL LENSING OF QUASAR 0957+561 AND THE DETERMINATION OF H_0 *

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ABSTRACT

We present results of a deep imaging study of the cluster lensing the double quasar Q0957+561. Using data obtained at KPNO and CFHT we have detected distortions in the lensed blue background galaxy population. From these arclet distortions we have constructed a map of the mass density in the field of the double QSO. We use this map to provide constraints on the mass concentrations responsible for the lensing. Using these constraints in conjunction with mass models and the known time delay between the A and B images we place limits on the value of the Hubble constant.

1. INTRODUCTION

The double quasar 0957+561 was the first discovered instance of multiple imaging via gravitational lensing and has been observed in the radio, optical, infrared and X-ray. It is the only gravitational lens system for which the magnification matrix and the time delay between the two images are well constrained. This is at present the only system for which one can follow the suggestion of Refsdal (1966) to derive the Hubble constant from the time delay between multiple images. Unfortunately the lens geometry cannot be explained using only the galaxy G1 found between the quasar images. The galaxy cluster surrounding G1 is an important deflector as well and this complication has so far precluded construction of a unique, satisfactory model of the lens, reducing the accuracy of the derived Hubble constant. To address this problem have obtained deep images of the system at CFHT. The cluster is sufficiently massive to cause distortions on distant background galaxy images. We have used a mass map derived from lensing distortions to improve the accuracy of the cluster center location and place new limits on H_0.

2. THE TIME DELAY

To derive the Hubble constant using the double quasar one must measure the difference in the light travel time along the paths from the source to the observer. This has been done in the radio and optical by monitoring the two quasar images. Vanderriest *et al.*(1989) obtain a value of 415 ± 20 days based on optical data. Schild (1991) obtains a value of 404 ± 10 days also based on optical monitoring. Press *et al.*(1992) using a global χ^2 statistic obtain a value 536 ± 12 days using

* Based on observations collected at the Canada-France-Hawaii Telescope at Mauna Kea, Hawaii, USA

the same optical data. They emphasize that smooth interpolation followed by cross correlation is an unreliable technique. From radio monitoring studies Lehar *et al.*(1991) conclude that the time delay is 513 ± 40 days. We conclude that the true value of the time delay lies between 415 and 540 days.

3. THE LENS PROPERTIES

The galaxy principally responsible for the lensing (G1) lies between the two quasars about 1″ north of the B image. It has a redshift of 0.36. Bernstein *et al.* (1993) have published photometry of this galaxy. They find that the surface brightness profile is well fit by a power law with index $n = -1.94 \pm 0.06$. The profile is also well fit by a de Vaucouleurs law with $R_e = 4.5 \pm 0.65''$. The central surface brightness is $I_e = 23.7 \pm 0.1$ R mag arcsec $^{-2}$. The position angle of the galaxy may twist slightly about a mean value of 55°. The I_e and R_e values quoted above are typical for brightest cluster member ellipticals or cD's. Applying the Faber-Jackson relation to these data one infers a velocity dispersion for G1 of ~ 400 km s^{-1} . From spectroscopic observations Rhee (1991) derives a velocity dispersion 300 ± 50 km s^{-1} for G1. This is somewhat less than predicted from the Faber Jackson relation but it is known that brightest cluster ellipticals tend to have lower velocity dispersions than the Faber-Jackson law would suggest.

The cluster in which the galaxy G1 is found has a velocity dispersion of $500 \sim 700$ km s^{-1} . From the galaxy distribution the cluster appears to be located 20-30″ west of the B image, it has an estimated core radius of 30″ and ellipticity of 0.55 .

4. MODELS OF THE MASS DISTRIBUTION

Based on the observations described above we have derived models for the galaxy and cluster lensing the double quasar. We model the galaxy mass to have the profile $\Sigma_0(r) = 0.033(r/3)^n$ in the range $0.3'' \leq r \leq 30''$, the power law index is allowed the following range $-1.9 \leq n \leq -0.5$. There are 4 free parameters for the galaxy model: the velocity dispersion, the ellipticity, the galaxy position angle and the power law index. The cluster is modeled to first order in the ellipticity as an expansion of an elliptical pseudo-isothermal sphere.

$$\phi_c = b_c(s_c^2 + r^2)^{\frac{1}{2}} + \frac{\gamma}{3} b_c r^2 (s_c^2 + r^2)^{-\frac{1}{2}} \cos 2(\theta - \theta_\gamma)$$

The 6 free parameters are: the cluster velocity dispersion, the cluster core radius, the cluster ellipticity, the cluster position angle the distance between the cluster center and the galaxy center and the position angle of the line joining the cluster center to the galaxy center. The cluster maps show that the cluster potential is not perfectly smooth. This can be taken into account by adding a shear component to the two components listed above. The shear component has two parameters the magnitude of the shear and its position angle. The effect of the shear may be taken as some indication of the changes in the models that would result from the addition of lumps to the mass distribution.

5. THE OBSERVATIONS

The observations were made with FOCAM and the SAIC CCD at CFHT in January 1994. We obtained a 3 hour integration in B band and a 4 hour integration in I-band. Sky flats of high precision were secured from dithered exposures on a control field. The B image is shown in figure 1. Figure 2 shows a map of the surface mass density of the matter lensing Q0957+561. This map is obtained by inverting the estimated shear field inferred from the observed shapes and orientations of background galaxies.

6. CONSTRAINTS ON THE MASS MODELS

From the map of the mass distribution we can locate the center of the cluster relative to the lensing galaxy. This is a key parameter for the determination of H_0. We measure the cluster center position to be at a distance (r_c) of 9 arcseconds from the lensing galaxy in the direction $\theta_c = 193°$. In a recent study Dahle et al. (1994) using deep images obtained with the Nordic Optical Telescope find r_c= 6 arcseconds and $\theta_c = 123°$. The uncertainties associated with these numbers are ~3 arcseconds in the distance and ~ 30° for the position angle.

7. CONCLUSION

From the constraints on two of the parameters of our model of the cluster and galaxy lensing Q0957+561 we can infer limits on the Hubble constant. Using the distortion of background galaxies we have derived a map of the mass distribution lensing the QSO. We have used this map to locate the position of the cluster lensing the QSO. The two parameters are the position angle of the vector joining the first ranked galaxy (G1) to cluster center, and the length of this vector. By limiting the range in values that these two parameters can have we eliminate all models except those having H_0 less than 70 km/s/Mpc.

ACKNOWLEDGEMENTS

George Rhee acknowledges support from a UNLV Barrick travel grant and the UNLV Physics department Bigelow fund.

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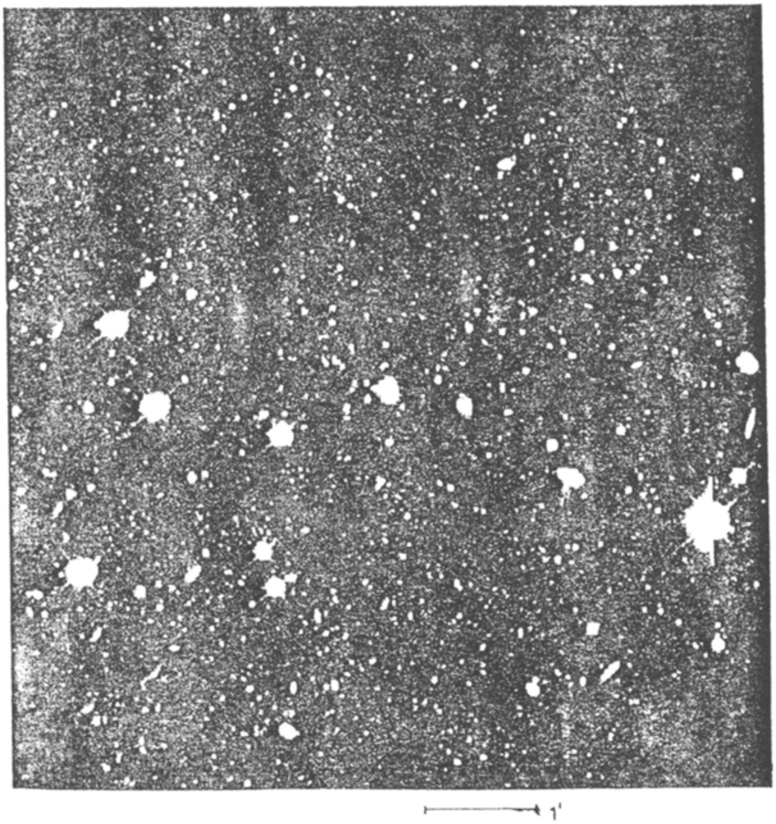

Fig. 1. B band exposure of the 0957 field. CFHT FOCAM.

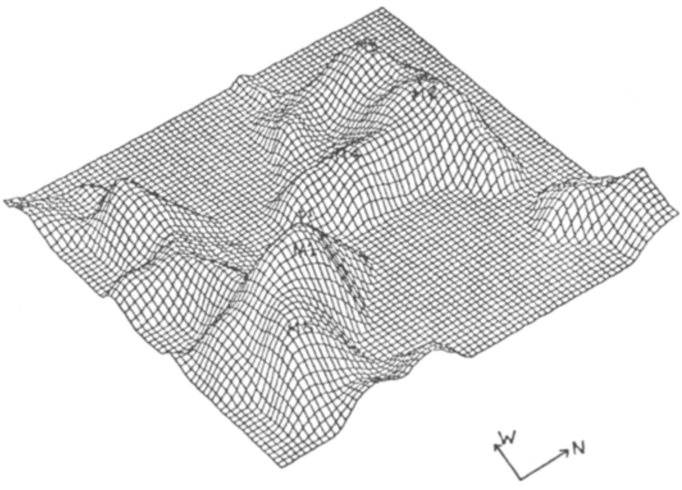

Fig. 2. Map of the surface mass density of the matter lensing Q0957+561