NEW "EINSTEIN CROSS" GRAVITATIONAL LENS CANDIDATES IN HST WFPC2 SURVEY IMAGES

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Abstract. We report the serendipitous discovery of quadruple gravitational lens candidates using the Hubble Space Telescope. We have so far discovered two good examples of such lenses, each in the form of four faint blue images located in a symmetric configuration around a red elliptical galaxy. The high resolution of HST has facilitated the discovery of this optically selected sample of faint lenses with small ($\sim$1") separations between the (I$\sim$ 25 − 27) lensed components and the much brighter (I$\sim$ 19 − 22) lensing galaxies. The sample has been discovered in the routine processing of HST fields through the Medium Deep Survey pipeline, which fits simple galaxy models to broad band filter images of all objects detected in random survey fields using WFPC2.

1. INTRODUCTION

Einstein (1936) computed the gravitational deflection of light by massive objects and showed that an image can be highly magnified if the observer, source and the deflector are sufficiently well aligned. However, the angular resolution available then to ground based optical telescopes made him remark that "there is no great chance of observing this phenomenon". Zwicky (1937) showed that "extragalactic *nebulae* offer a much better chance than *stars* for the observation of gravitational lens effects".

Over the last decade a number of lensed QSO candidates were located in radio surveys and subsequently the associated lensing galaxies were optically identified (See Schneider, Ehlers and Falco 1992 for review). Huchra et al. (1985) discovered the "Einstein cross" at the center of the bright

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(V=14.6) galaxy 2237+0305, an object in the Center for Astrophysics redshift survey: this lens is considered unique because of the very low probability of alignment of a QSO within 0.″3 of the center of a nearby (z=0.04) galaxy.

The Medium Deep Survey (MDS) is a Hubble Space Telescope (HST) key project, which relies exclusively on the efficient use of parallel observing time to take images of random fields which are several arcminutes away from the primary targets of other HST instruments (Griffiths et al. 1994). Similar observations have been made by the Guaranteed Time Observers (GTO) in parallel mode, in conjunction with primary GTO exposures. In addition to these two parallel surveys, a major 'strip' survey was performed (Groth et al. 1995) using the WFPC2 in primary mode. With the refurbished HST WFPC2 optics we have now been able to start an optical survey for gravitational lenses centered on field galaxies in the magnitude range I= $19-23$, searching for background field galaxies which are lensed into components with magnitudes I= $23-27$.

2. OBSERVATIONS

In cycle 4 of HST observations, from January 1994 to June 1995, the MDS and GTO parallel datasets have comprised about 35 and 15 independent high galactic latitude fields, respectively, with at least two WFPC2 exposures in each of the F606W(V) and F814W(I) filters for each field. The 42 arc min long Groth-Westphal strip (Groth et al. 1995) consists of 28 contiguous WFPC2 fields centered at b =+60.°25 and l =96.°35. The observations, covering a total area about 120 square arc minutes, were taken between 7 March and 9 April 1994. After the one-year proprietary period, they were obtained from the HST archive and calibrated, stacked and processed in exactly the same way as fields obtained for the HST Medium Deep Survey. A root-mean-square(rms) error image reflecting both the excluded cosmic rays and the flat field was created and used in the object detection and subsequent image analysis algorithms.

In order to search for serendipitous objects and to correct any errors in the automated object detection process caused by confusion of overlapping or very bright images, the fields have been examined by eye. During this process, it was noticed that the I=19.7 elliptical galaxy (HST14176+5226) was flanked by four fainter images which were all at about the same magnitude and color and much bluer than the central elliptical which had a half light radius of 1.″2 (see Figure 1). The companion objects (V$\sim$ 26) were about 1.″2 and 1.″6 distant from the center of the elliptical galaxy along the major and minor axes respectively. Furthermore, the objects on the cross appeared to be stretched in a direction at right angles to the line joining

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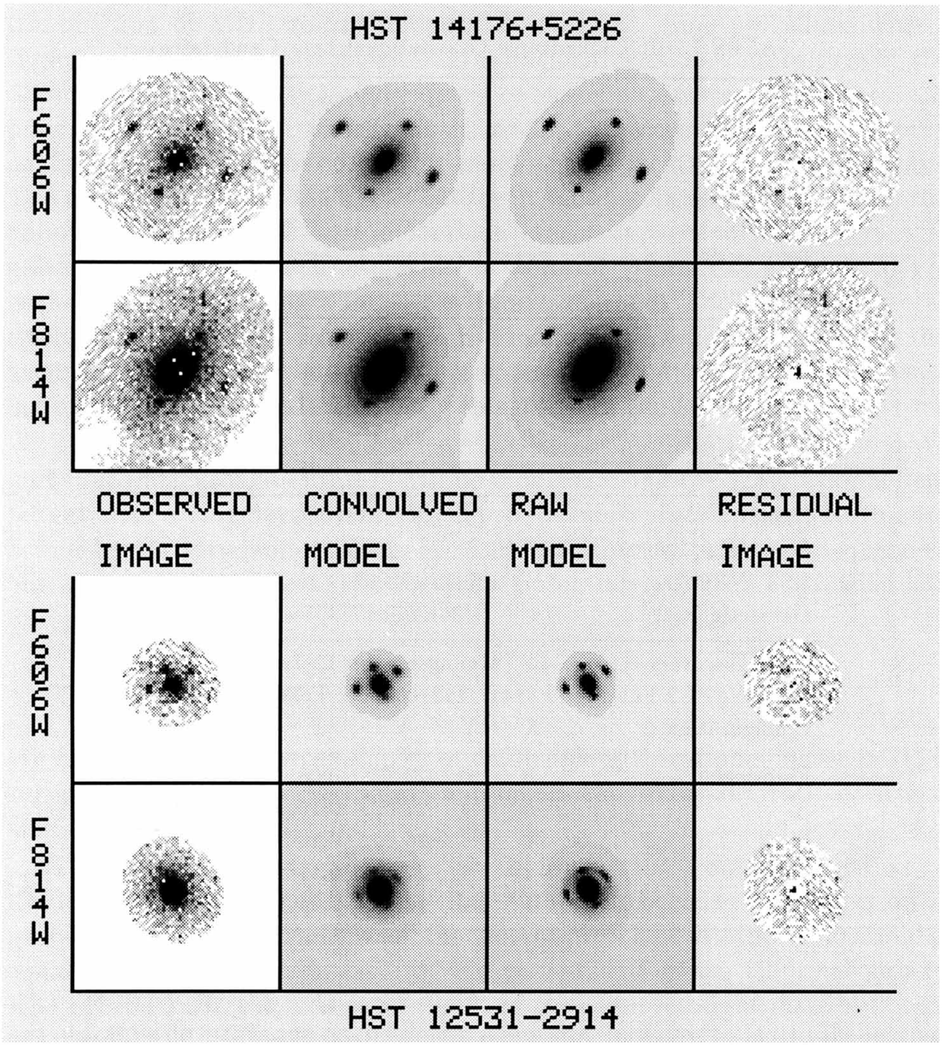

Figure 1. The maximum likelihood fits to the two gravitationally lensed images. The images are displayed as analyzed, without any interpolation over bad pixels. Each box is 6$''$.4 square. The residuals show only a very faint trace of the subtracted images. Note that the convolution with the WFPC2 PSF does influence the appearance of the lensed images. The faint lensed images are blue and better resolved in F606W, even though the image exposure times in the F814W filter are 50% longer.

them to the center of the elliptical galaxy.

A second fainter (I=21.8) and smaller (half light radius 0$''$.2) elliptical galaxy (HST12531−2914) was discovered when inspecting the residuals of the maximum likelihood model fits to galaxies in a deep MDS field urz00. Since the faint companion objects (V$\sim$ 27) are only about 0$''$.5 from the

TABLE 1. HST Quadruple Gravitational Lens Candidates

Name	HST14176+5226					
Equatorial(J2000)	14:17:36.3		+52:26:44		V_3=32°.93	
HST WFPC2	Groth GTO:5090 11-Mar-1994					
Dataset[g][x,y]	U26X0801T[3][242,700]					
MDS Discovery	Eric J. Ostrander 02-May-1995					
HST WFPC2 Filter	F814W 4x1100s			F606W 4x700s		
Configuration	X	Y	V	±	V−I	±
Elliptical	0	0	21.68	0.04	1.97	0.04
A	−11	11	25.63	0.06	0.51	0.10
B	18	−4	25.77	0.07	0.39	0.11
C	10	12	25.99	0.08	0.52	0.13
D	−3	−9	25.97	0.08	0.42	0.14
Name	HST12531−2914					
Equatorial(J2000)	12:53:06.7		−29:14:30		V_3=127°.77	
HST WFPC2	Griffiths GO:5369 15-Feb-1995					
Dataset[g][x,y]	U26K7G04T[3][755,326]					
MDS Discovery	Myungshin Im 12-Jun-1995					
HST WFPC2 Filter	F814W 4x2100s			F606W 3x1800s		
Configuration	X	Y	V	±	V−I	±
Elliptical	0	0	23.77	0.06	1.95	0.07
A	−6	−2	27.02	0.15	0.25	0.28
B	6	3	26.89	0.15	0.43	0.23
C	−2	4	26.72	0.11	0.34	0.21
D	3	−4	27.51	0.24	0.82	0.34

central elliptical, they had not been resolved as separate objects by the automated object detection algorithm. A "southern cross" just in time for presentation at this IAU symposium in Melbourne, Australia.

The observed image configuration, magnitudes and colors are given in Table 1. The magnitudes of the components were computed using a 0″.3 square aperture, and corrected to total magnitudes assuming a point source. The offsets (X,Y) are in WFC 0″.1 pixels from the centroid of the respective elliptical galaxy.

3. THE LENS MODEL

The details of the model fitting are given in Ratnatunga et al. (1995). Since we had already developed software for 2-dimensional 'disk + bulge' de-

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composition of MDS galaxy images, we used the same procedure with a slight modification to do 'bulge + gravitational lens' decomposition of the observed light distribution. Given a set of model parameters, we generate 2-dimensional images for the elliptical and the source galaxies. The expected configuration of the lensed images is ray-traced by numerical integration. The elliptical lens and the lensed source images are then convolved with the adopted WFPC2 point spread function, and compared with the observed galaxy image. The evaluated likelihood function (similar to a weighted χ^2) is then minimized using a quasi-Newtonian method. This procedure iteratively converges simultaneously on the maximum likelihood model for the lensing elliptical galaxy and the source, so as to produce the observed lensing galaxy and the configuration of images from the lensed source.

The inferred elliptical mass distribution is significantly flat (0.40). We find that the lens configuration can be modeled using the gravitational field potential of a singular isothermal ellipsoidal mass distribution (Kormann, Schneider & Bertelmann 1994). We find that this potential is adequate to obtain a fit better than any of the other potentials we tried, even using less free parameters.

4. CONCLUSIONS

We have discovered two examples of quadruple gravitational lenses in HST survey data, one in the MDS data and one in the archived Groth-Westphal GTO survey.

The lensed image components are more distant from the centroid of the lensing elliptical galaxy along the minor axis because the deflection is proportional to the gradient of the potential. The ratio in separation is equal to the inverse axis ratio of the potential. For the elliptical galaxy HST14176+5226, the axis ratio (0.68) of the observed light distribution is practically the same as that of the potential (0.74), and the orientation is the same within 10 ± 2 degrees. A model independent inference is that the stars are a trace population following the gravitational potential. The Mass/Light distribution, increases radially outwards.

The critical radii of HST14176+5226 and HST12531+2914 are $1\overset{''}{.}5$ and $0\overset{''}{.}6$, in each case larger than the half light radii of $1\overset{''}{.}2$ and $0\overset{''}{.}2$ for these galaxies respectively. The distance of the intrinsic source from the centroid of the lens needs to be less than about 0.15 of the critical radius for the creation of a quadruple image. The impact parameters for these two objects are about 0.08 and 0.09 of the critical radius.

These represent the first discoveries of lenses using the high resolution of HST - indeed, apart from the exceptional original Einstein cross discovered by Huchra et al. (1985), they represent the first discoveries of field-galaxy gravitational lenses via the systematic study of optical images.

These objects would have been very difficult discoveries from the ground except under conditions of excellent seeing. We have not as yet observed these galaxies spectroscopically. The redshift of the lensed components in HST12531−2914 is probably a challenging observation for the Keck telescope in excellent seeing.

From the observed numbers of bright elliptical galaxies observed in the GTO survey strip (300 to I = 22), the numbers of faint objects in the fields (8000 to I = 26), and the expected cross-sections, we estimate that we should find one quadruple lens in every $20-30$ WFPC2 fields surveyed. The number that has been discovered so far is therefore consistent with our expectations.

An on-going systematic and careful inspection, looking very specifically for possible gravitational lens candidates in the shallower MDS and GTO parallel fields is in progress in order to expand the sample. As further MDS data are taken in Cycle 5 and subsequent cycles, they will be examined for similar spectacular lenses, and also for more common lenses consisting of arcs or two or three components, to obtain a statistically representative sample of HST gravitational lens candidates, for statistical study.

These are a new class of gravitational lens candidates in which the cosmologically distant lens is a relatively bright elliptical galaxy with well understood properties. If a significant sample could be found and observed spectroscopically for redshifts, they will be very useful cosmological probes.

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