

## NEW “EINSTEIN CROSS” GRAVITATIONAL LENS CANDIDATES IN *HUBBLE SPACE TELESCOPE* WFPC2 SURVEY IMAGES

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Received 1995 June 26; accepted 1995 August 24

### ABSTRACT

We report the serendipitous discovery of “Einstein cross” gravitational lens candidates using the *Hubble Space Telescope* (*HST*). 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 ( $I \sim 25\text{--}27$ ) lensed components and the much brighter ( $I \sim 19\text{--}22$ ) 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 broadband filter images of all objects detected in random survey fields using WFPC2.

We show that the lens configuration can be modeled using the gravitational field potential of a singular isothermal ellipsoidal mass distribution. With this model the lensing potential is very similar, both in ellipticity and orientation, to the observed light distribution of the elliptical galaxy, as would occur when stars are a tracer population. The model parameters and associated errors have been derived by two-dimensional analysis of the observed images. The maximum likelihood procedure iteratively converges simultaneously on the model for the lensing elliptical galaxy and the source of the lensed components. A systematic search is in progress for other gravitational lens candidates in the *HST* Medium Deep Survey. This should eventually lead to a good statistical estimate for lensing probabilities and enable us to probe the cosmological parameters.

*Subject headings:* cosmology: observations — gravitational lensing — surveys

### 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, & Falco 1992 for review). Huchra et al. (1985) discovered the “Einstein cross” at the center of the bright ( $V = 14.6$ ) 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. With the refurbished WFPC2 optics on the *Hubble Space Telescope* (*HST*), we have now been able to start an optical survey for gravitational lenses centered on field galaxies in the magnitude range  $I = 19\text{--}23$ , searching for background field galaxies that are lensed into components with magnitudes  $I = 23\text{--}27$ .

The Medium Deep Survey (MDS) is an *HST* key project that relies exclusively on the efficient use of parallel observing time to take WFPC2 images of random fields that 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) using

WFPC2 in parallel mode, in conjunction with primary GTO exposures. The GTO parallel observations have been made available to all *HST* GTO teams. In addition to these two parallel surveys, a major “strip” survey was performed (Groth et al. 1994) using the WFPC2 in primary mode.

For the study of galaxies in the parallel surveys (MDS and GTO), we exclude fields at low Galactic latitude and those inside Galactic globular clusters or Local Group galaxies, where the data are dominated by stellar images. The Groth-Westphal “strip” and other fields with both  $I$  and  $V$  observations are processed through the MDS pipeline as they become available via the *HST* archive after the 1 yr proprietary period. We fit simple galaxy models to images of all extended objects detected, using the maximum likelihood method for determination of the best-fit galaxy parameters (Ratnatunga, Griffiths, & Casertano 1995). In view of the large number of fields, most of the processing is automated except for a manual stage to correct for errors in the detection and resolution of objects and in the final inspection of the fitted models and residual images.

Serendipitous discoveries have always been a major potential of the Medium Deep Survey. Previous results from the MDS have focused on the systematic measurements of stars and galaxies (see Griffiths et al. 1995 for a summary and a bibliography for the MDS). Although an unusual object was discovered in the very first MDS image from WFPC2 (Glazebrook et al. 1994), this was probably a protogalaxy in formation at  $z = 0.7$  with superluminous starburst knots, rather than a gravitational lens as originally suspected. The observations presented in this Letter represent the first discovery of a relatively new class of objects.

TABLE 1  
*HST* "EINSTEIN CROSS" GRAVITATIONAL LENS CANDIDATES

Parameter	HST 14176+5226				HST 12531-2914			
Equ(J2000).....	14 <sup>h</sup> 17 <sup>m</sup> 36 <sup>s</sup> .3	+52°26'44"	$V_3 = 32^{\circ}93$		12 <sup>h</sup> 53 <sup>m</sup> 06 <sup>s</sup> .7	-29°14'30"	$V_3 = 127^{\circ}77$	
<i>HST</i> WFPC2 .....	Groth GTO:5090 1994 Mar 11				Griffiths GO:5369 1995 Feb 15			
Data set [g][x, y] .....	U26X0801T[3][242,700]				U26K7G04T[3][755,326]			
Configuration.....	<i>X</i>	<i>Y</i>	<i>V</i>	<i>V-I</i>	<i>X</i>	<i>Y</i>	<i>V</i>	<i>V-I</i>
Elliptical.....	0	0	21.68 ± 0.04	1.97 ± 0.04	0	0	23.77 ± 0.06	1.95 ± 0.07
A.....	-11	11	25.63 ± 0.06	0.51 ± 0.10	-6	-2	27.02 ± 0.15	0.25 ± 0.28
B.....	18	-4	25.77 ± 0.07	0.39 ± 0.11	6	3	26.89 ± 0.15	0.43 ± 0.23
C.....	10	12	25.99 ± 0.08	0.52 ± 0.13	-2	4	26.72 ± 0.11	0.34 ± 0.21
D.....	-3	-9	25.97 ± 0.08	0.42 ± 0.14	3	-4	27.51 ± 0.24	0.82 ± 0.34

## 2. OBSERVATIONS

Prior to 1993 December, the aberrated data from *HST* and WFPC could not be used for the purposes of the present study. In cycle 4 of *HST* observations, from 1994 January to 1995 June, the MDS and GTO parallel data sets 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. These fields have all been processed through the MDS pipeline. In addition, there are about 30 and 70 fields in these surveys, respectively, for which one or both of the filters has only one exposure; in these latter fields, unbiased cosmic-ray cleaning is a more difficult task, and processing of these fields is not yet completed.

The 42' long Groth-Westphal strip (Groth et al. 1995) consists of 28 contiguous WFPC2 fields centered at  $b = +60^{\circ}25$  and  $l = 96^{\circ}35$ . The observations, covering a total area about 120 arcmin<sup>2</sup>, were taken between 1994 March 7 and April 9. 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. Full details of the catalog and statistical analysis of the distributions of magnitude, color, half-light radius, axis ratio, and position angle and location will be described in other publications.

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 one of us (E. J. O.) by eye. During this process, it was noticed that the  $I = 19.7$  elliptical galaxy (HST 14176+5226) was flanked by four fainter images that 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 Fig. 1 [Pl. L1]). 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 arcs. This galaxy was thus clearly identified as a very strong gravitational lens candidate.

A second fainter ( $I = 21.8$ ) and smaller (half-light radius 0".2) elliptical galaxy (HST 12531-2914) was discovered by one of us (M. I.) 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 central elliptical, they had not been

resolved as separate objects by the automated object detection algorithm.

The observed image configuration, magnitudes and colors are given in Table 1. The magnitudes of the components were computed using a 0.3 arcsec<sup>2</sup> and corrected to total magnitudes assuming a point source. The magnitude of the elliptical is from the model fit. The offsets (*X*, *Y*) are in WFC 0".1 pixels from the centroid of the respective elliptical galaxy.

## 3. THE LENS MODEL

In this Letter we will limit the model analysis to gravitational lenses described by singular isothermal elliptical potentials (Kormann, Schneider, & Bartelmann 1994), which provide a sufficiently accurate representation for our purposes. We adopt their definitions and notations in this Letter.

Since we had already developed software for two-dimensional "disk + bulge" decomposition of MDS galaxy images, we used the same procedure with a slight modification to do "bulge + gravitational lens" decomposition of the observed light distribution. 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.

For the light distribution of the elliptical, we used the seven parameters that we routinely use for the analysis of a galaxy image with a single component: local sky, location (*x*, *y*), total magnitude, half-light radius, axis ratio, and position angle. The lensed source was defined by four parameters: location (*s<sub>x</sub>*, *s<sub>y</sub>*) relative to the elliptical, and intrinsic magnitude and half-light radius. Since the morphology of the source was very poorly constrained, it was assumed to be bulge-like with spherical symmetry. The lens is defined by the critical radius ( $\xi_0$ ) and the axis ratio of the mass distribution. An optional parameter is used to measure the difference in the orientation between the mass and the observed light of the lens.

Given a set of model parameters, we generate two-dimensional images for the elliptical and the source galaxies. The expected configuration of the lensed images is ray-traced by numerical integration. To improve the accuracy of the numerical integration, the image is evaluated using a pixel size smaller than the real one, such that the image fills a 64 × 64 pixel array. The elliptical lens and the lensed source images are then convolved with the adopted *HST* WFPC2 point spread function from TinyTim (Krist 1994). The convolved image is spatially integrated to the WFC pixel size of 0".1 and is then compared with the observed galaxy image. The likelihood function is defined as sum over all pixels of the logarithm



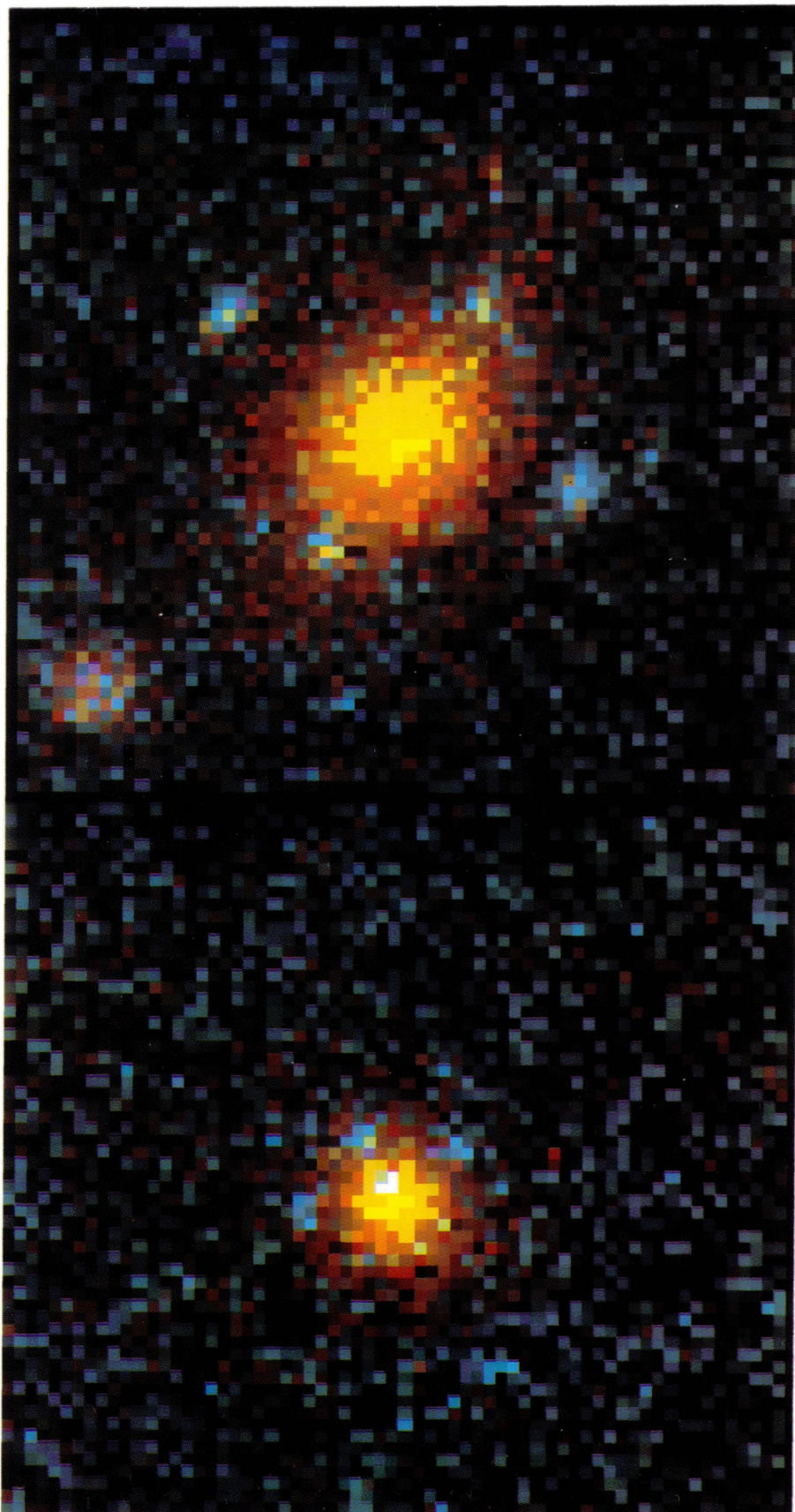


FIG. 1.—“Artistic color” images of “Einstein cross” gravitational lens candidates HST 14176+5226 (*upper*) and HST 12531–2914 (*lower*) from WFPC2 Survey images in filters F606W and F814W. Each region is  $6''.4$  square. The fourth component of HST 12531–2914 is seen more clearly on the F606W image on plate 2.

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TABLE 2  
MAXIMUM LIKELIHOOD ESTIMATES FOR LENS CANDIDATES

Parameter	HST 14176+5226		HST 12531-2914	
	F814W	F606W	F814W	F606W
HST WFC2 Filter .....	F814W	F606W	F814W	F606W
Exposure(s) .....	4 × 1100	4 × 700	4 × 2100	3 × 1800
Sky magnitude (arcsec <sup>2</sup> ) .....	22.281 ± 0.003	22.807 ± 0.003	21.950 ± 0.004	22.517 ± 0.004
Total magnitude of elliptical .....	19.71 ± 0.01	21.68 ± 0.04	21.82 ± 0.03	23.77 ± 0.06
<i>X</i> centroid 0".1 pixel .....	242.41 ± 0.02	242.28 ± 0.03	754.83 ± 0.02	754.78 ± 0.03
<i>Y</i> centroid 0".1 pixel .....	700.02 ± 0.02	700.23 ± 0.03	325.91 ± 0.02	326.23 ± 0.04
Half-light radius (arcsec) .....	1.200 ± 0.006	1.350 ± 0.058	0.199 ± 0.013	0.222 ± 0.023
Position angle light (degrees) .....	-37.8 ± 0.8	-41.8 ± 0.2	24.7 ± 1.5	22.6 ± 0.5
Axis ratio of the light .....	0.68 ± 0.01	0.65 ± 0.03	0.84 ± 0.03	0.73 ± 0.07
Magnitude of lensed source .....	25.76 ± 0.2	26.1 ± 0.2	27.4 ± 0.2	27.4 ± 0.2
Source <i>X</i> offset 0".1 pixel .....	0.28 ± 0.06	0.12 ± 0.03	0.28 ± 0.07	0.47 ± 0.04
Source <i>Y</i> offset 0".1 pixel .....	-1.24 ± 0.07	-1.36 ± 0.04	-0.23 ± 0.09	-0.55 ± 0.03
Critical Radius (arcsec) .....	1.508 ± 0.008	1.511 ± 0.005	0.648 ± 0.010	0.646 ± 0.006
Axis ratio lens mass .....	0.395 ± 0.018	0.370 ± 0.006	0.64 ± 0.04	0.369 ± 0.011
Source half-light (arcsec) .....	0.016 ± 0.009	0.018 ± 0.010	0.053 ± 0.013	0.031 ± 0.025
Lens rotation (degrees) .....	8.5 ± 0.8	12.8 ± 0.2	0.00 ± Fixed	0.00 ± Fixed

of the probability of the observed value, assuming that it has a Gaussian error distribution with respect to the model. This is similar to a weighted  $\chi^2$  and is then minimized using a quasi-Newtonian method.

#### 4. MAXIMUM LIKELIHOOD ESTIMATES

The results of the maximum likelihood estimates and errors are summarized in Table 2 and the corresponding images are shown in Figure 2 (Plate L2) for both of the galaxies analyzed. The rms errors are estimated from the covariance matrix, which is derived by inverting the Hessian at the maximum of the likelihood function. Note that the model parameters fitted independently to the F814W and F606W band images are very similar and well within the statistical errors and expected variations due to color. Since the fainter lensed images are blue and better resolved in F606W, the error estimates are smaller in this filter, even though the image exposure times in the F814W filter are 50% longer.

The critical radii of HST 14176+5226 and HST 12531-2914 are 1".5 and 0".6, in each case larger than the half-light radii of 1".2 and 0".2 for these galaxies, respectively. 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 the distance between components at opposite ends of the cross is equal to the inverse axis ratio of the potential. 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.

In both cases the source has a half-light radius which is smaller than a WFC 0".1 pixel. However, the fact that the maximum likelihood estimate converged to a small but finite intrinsic source half-light radius appears to indicate that it is extended. We find a value for the half-light radius to be similar to those of field galaxies at the magnitude of the lensed source (see Casertano et al. 1995; Im et al. 1995), i.e., within the range 0".04-0".40.

A significantly better fit (99.9%) is obtained for HST 14176+5226 by relaxing the constraint that the orientation of the lens mass is the same as that of the observed light. The difference is practically independent of the model used and is  $8.5 \pm 0.8$  in F814W and  $12.9 \pm 0.2$  in F606W. Such a small rotation might be expected from projection effects (see Franx,

Illingworth, & de Zeeuw 1991). As shown in Figure 3, the axis ratio (0.68) of the light from the elliptical galaxy HST 14176+5226 is practically the same as that of the potential (0.74). The inferred elliptical mass distribution is significantly flatter than this (0.40).

Using the observed  $V-I$  colors, apparent magnitudes, and half-light radii, we can estimate the redshift for each of the lens elliptical galaxies to be  $z(D_d) = 0.7 \pm 0.1$  (see, e.g., Connolly et al. 1995). Using these redshifts, the luminosities of the elliptical galaxies can be estimated for the plausible range of evolutionary and  $K$ -corrections and the value of  $\Omega$ , and thus the velocity dispersion  $v$  from the relation of Faber & Jackson (1976). We find that the observed critical radii  $\xi_0 = 4\pi(v/c)^2 D_d D_{ds}/D_s$  are more probable for  $\Omega < 1$  for a source redshift smaller than  $z(D_s) < 3$  (Guhatakurta, Tyson, & Majewski

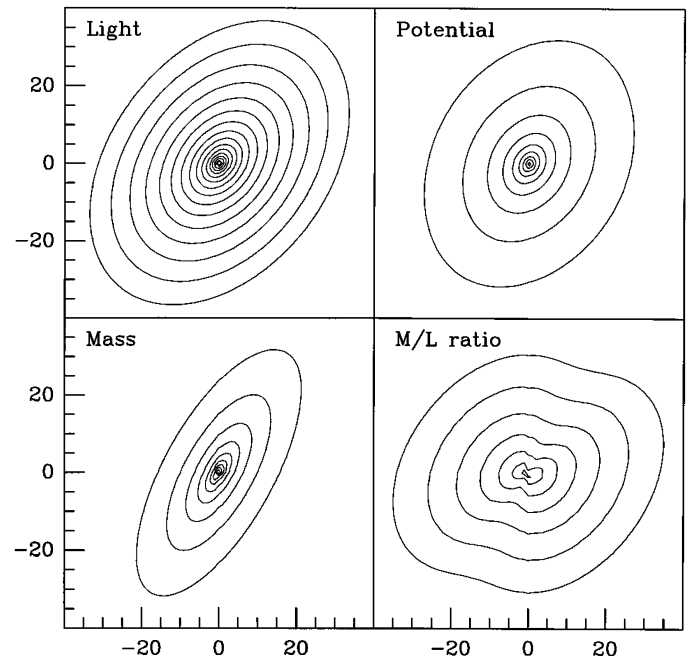


FIG. 3.—The observed light distribution of HST 14176+5226, the maximum likelihood potential according to the elliptical mass model, and the resulting mass/light distribution, which is rounder (axis ratio = 0.82) and increases radially outward. All the contours have been drawn at constant 0.5 mag intervals, and units are 0".1 WFC pixels.



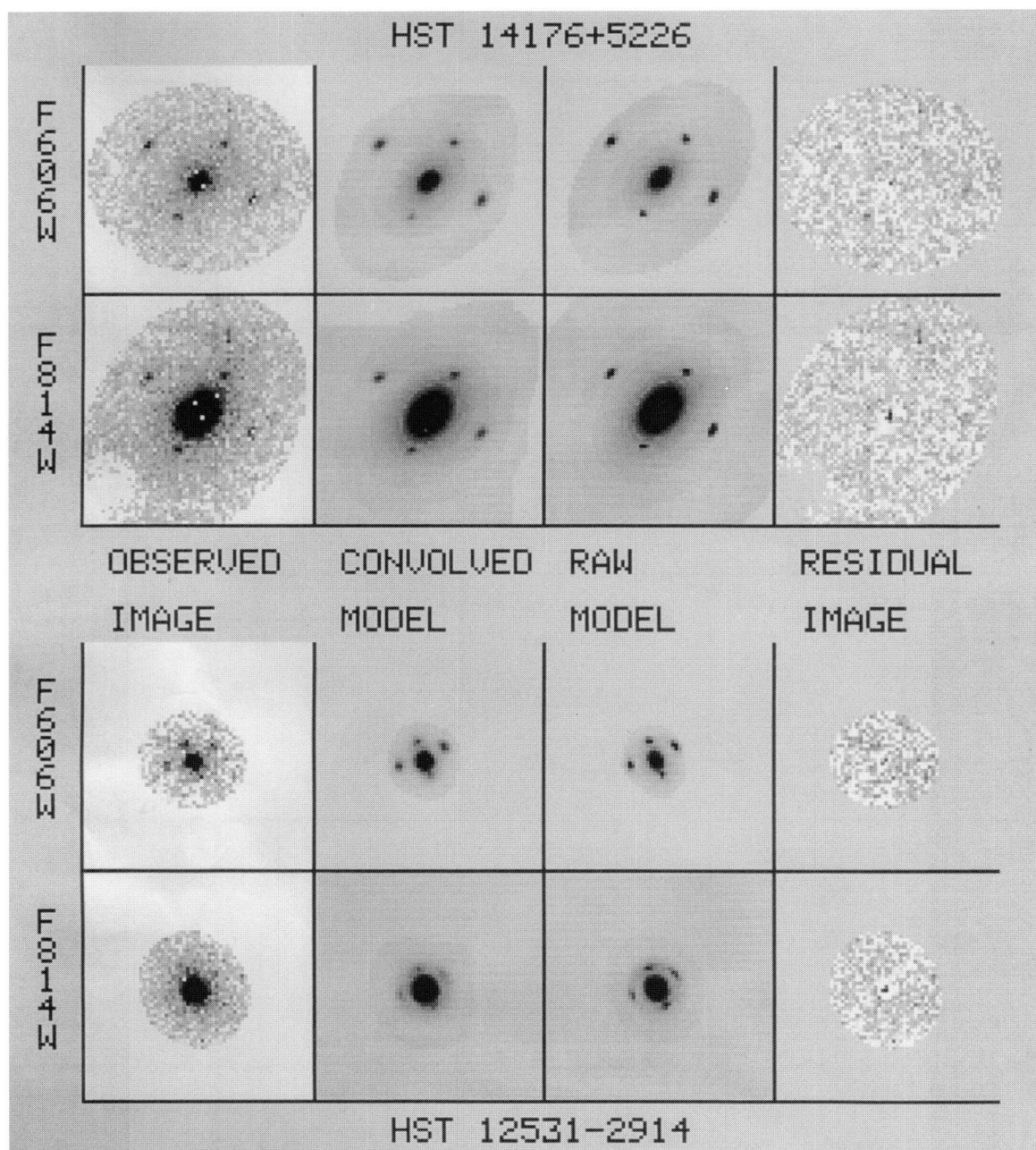


FIG. 2.—The maximum likelihood fits to the two gravitationally lensed images. The images are displayed as analyzed, without any interpolation over bad pixels. Each box is 6'4 square. The residuals show only a very faint trace of the subtracted images. Note that the convolution with the WFPC2 PSF does influence the appearance of the lensed images. See the text for details.

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1990). For more detailed discussions, see Im, Ratnatunga, & Griffiths (1995).

### 5. CONCLUSIONS

We have discovered two examples of “Einstein cross” gravitational lenses in *HST* survey data, one in the MDS data and one in the archived Groth-Westphal GTO survey. The lens configurations show that the stars responsible for the light distribution of these elliptical galaxies are a trace population following the gravitational potential. The mass-to-light ratio increases radially outward.

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. They 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.

These objects would have been very difficult discoveries from the ground except under conditions of excellent seeing. Indeed, CCD frames taken at the KPNO 4 m prime focus (Connolly 1995) do not show the cross objects flanking the elliptical galaxy HST 14176+5226. We have not as yet observed these galaxies spectroscopically. The redshift of the

lensed components in HST 12531–2914 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 ongoing systematic and careful inspection of the MDS fields, 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.

This Letter is based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. The Medium-Deep Survey is funded by STScI grant G02684. We gratefully acknowledge Lyman Neuschaefer for help with the MDS pipeline and many helpful discussions, the anonymous referee from many useful suggestions, and Tom Broadhurst for motivational comments.

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