

# *HST* Imaging Polarimetry of the Gravitational Lens

*FSC*10214 + 4724<sup>1</sup>

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## ABSTRACT

We present imaging polarimetry of the extremely luminous, redshift 2.3 *IRAS* source *FSC10214 + 4724*. The observations were obtained with *HST*'s Faint Object Camera in the F437M filter, which is free of strong emission lines. The 0.7 arcsec long arc is unresolved to 0.04 arcsec FWHM in the transverse direction, and has an integrated polarization of  $28 \pm 3$  percent, in good agreement with ground-based observations. The polarization position angle varies along the arc by up to 35 deg. The overall position angle is  $62 \pm 3$  deg east of north. No counterimage is detected to  $B = 27.5$  mag ( $3\sigma$ ), giving an observed arc to counterimage flux ratio greater than 250, considerably greater than the flux ratio of 100 measured previously in the *I*-band. This implies that the configuration of the object in the source plane at the *B*-band is different from that at *I*-band, and/or that the lensing galaxy is dusty.

*Subject headings:* Gravitational Lensing — Polarization — quasars:general — quasars:individual (*FSC10214 + 4724*) — elliptical galaxies

## 1. Introduction

gravitational lensing  
polarization  
imaging polarimetry

With a redshift of  $z = 2.286$ , *FSC10214 + 4724* remains the most distant object identified in the *IRAS* database. At the time of its initial discovery in 1991 (Rowan-Robinson *et al.*), it was estimated to have a luminosity well in excess of  $\sim 10^{14}L_{\odot}$ , most of which emerged in the far-infrared. Subsequent *HST* observations of *FSC10214 + 4724* (Eisenhardt *et al.* 1996, hereafter E96) with F814W have shown conclusively that the source is gravitationally lensed by a foreground elliptical galaxy, reducing its intrinsic luminosity to  $\sim 2 \times 10^{13}L_{\odot}$ . The redshift of the lensing galaxy has not yet been measured with certainty, but a value of 0.9 is favored by E96 and Lacey, Rawlings & Serjeant (1998). Millimeter and sub-millimeter line and continuum observations have shown that *FSC10214 + 4724* contains huge amounts of interstellar dust and gas and have raised the possibility that it is powered by a massive starburst (Downes, Solomon & Radford 1995; Rowan-Robinson *et al.* 1993; Scoville *et al.* 1995). Visual spectropolarimetry (Goodrich *et al.* 1996, hereafter G96) has revealed both a highly polarized (25 percent at  $0.44 \mu\text{m}$ ) continuum and polarized broad wings on the otherwise unpolarized emission lines. This is the polarimetric signature of a dust-embedded quasar, hidden from direct view but seen in reflection off of favorably placed cloud(s) of scattering dust. Therefore both stellar and non-thermal energy sources probably contribute to the luminosity of this object (Kroger *et al.* 1996, Lacey, Rawlings & Serjeant).

The present program makes use of the intervening gravitational lens as a microscope to study the structure of the inner regions of the quasar. At the F814W bandpass, the magnification is quite high ( $\sim 100$ , E96) suggesting that the background source is extremely close to a caustic of the lensing potential, so that small changes in the source position or size with wavelength will lead to differences in the position and structure of the image which could be resolved with *HST*. The principal features of the lensed image at F814W

are a 0.7 arcsec long arc which is unresolved ( $< 0.06$  arcsec) in the transverse direction, and an unresolved counterimage, about 1.6 arcsec away, with about 1 percent of the total flux of the arc. The absolute and relative positions of the arc and the counterimage, the extent and structure of the arc, and the relative brightness of the arc and the counterimage, are all sensitive to the structure of the source at the observed wavelength and its position relative to the caustic of the lensing potential (E96).

This paper reports the results of imaging polarimetry of *FSC10214 + 4724*, carried out in the continuum at an observed wavelength of 437nm using the *HST*'s Faint Object Camera (FOC). Subsequent papers will report the results of *HST* imaging of the source in narrow bands centered on a number of emission lines, providing information on the spatial distribution of gas in the narrow line region of the quasar.

At the *FSC10214 + 4724* redshift of  $z = 2.286$ , one 0.014 arcsec FOC pixel subtends  $100(60) h^{-1}$  pc for  $q = 0(0.5)$ , where  $h = H_o/100$  km s $^{-1}$  Mpc $^{-1}$  (where not otherwise specified, we assume  $H_o = 50$  km s $^{-1}$  Mpc $^{-1}$  and  $q = 0.5$ ). The FWHM of the *HST*'s point spread function at F437M is 0.042 arcsec.

## 2. Observations and Reduction

Imaging polarimetry was performed through three separate polarizers, referred to as POL0, POL60 and POL120, where the number indicates the position angle with respect to the detector in an instrumental coordinate system. A total of 15 orbits (35,055 seconds) of polarimetry data were obtained using the F437M filter in the FOC. The data were obtained in three visits. In the first visit, one orbit with each polarizer was obtained on 19 May, 1997. Each orbit began with a 200 second exposure on the  $B=19$  mag star 13.2 arcsec to the east (star A in E96), to allow registration of data in the three polarizers and to check the

PSF; the remainder of each orbit was spent on the arc. In the second visit, six orbits were obtained on 20-21 May 1997, with each orbit evenly divided between the three polarizers. The position angle orientations on the sky for the second visit were the same as for the first. In the third visit, six orbits were obtained on 29 June 1997 using the same strategy as in the second visit, except that the telescope was rotated around its line of sight so that the polarizer position angles were rotated 30 deg counterclockwise on the sky from first and second visit.

After standard processing provided by STScI, the FOC frames were corrected for spatial shifts introduced by the different polarizers. The shifts ( $\sim$  few pixels) were determined by measuring the position of star A relative to each polarization image. Additional corrections were also applied for pointing-offset (visit 2 and 3) and rotation (visit 3). The background for each individual frame was estimated and subsequently subtracted. The resulting frames were corrected for calibration and co-added for each visit. The Stokes parameters,  $I$ ,  $Q$  and  $U$ , were determined following Thompson & Robinson (1995). The overall polarization results were then obtained by averaging the Stokes parameters of the three visits.

### 3. Results

The F437M image of  $FSC10214 + 4724$  is shown in Figure 1, in grayscale, obtained from a straight co-add of frames from filters POL0 and POL120 for all three visits. These POL0 and POL120 data had a diffraction limited PSF with a FWHM of 0.042 arcsec. The POL60 data had a degraded PSF, and thus were left out for this intensity map. However, in the polarimetry analysis where POL60 images were included, and the pixels were binned to exchange higher spatial resolution for improvements in the signal-to-noise ratio, this degradation does not significantly affect the results.

### 3.1. Morphology

In the F437M FOC data, the *FSC10214+4724* arc has a length of  $\sim 0.7$  arcsec roughly along the east-west direction and is essentially unresolved ( $< 0.04$  arcsec) in the transverse direction. This is the same basic morphology seen by E96 in the F814W WFPC2 data. The tangential profile exhibits significant structure. Summed over  $3 \times 3$  pixels to improve the signal-to-noise ratio, the arc is seen to have two prominent peaks. The centroids of these two peaks are separated by at least 0.30 arcsec. This is significantly larger than the 0.24 arcsec separation observed in the F814W image.

The four objects seen in the F814W image which fall in the FOC field-of-view are the arc (referred to as component 1 by E96), the two lensing galaxies (components 2 and 3) and the counterimage (component 5). Components 1, 2 and 5 are shown as contours and labelled in Figure 1. The only object visible in the FOC data is the arc, as seen in grayscale in Figure 1. The absence of components 2 and 3 in the FOC data is expected from their measured spectral energy distribution (E96) and the depth of the FOC image (hereafter, E96's component 2 is referred to as the lensing galaxy). Most significantly, the counterimage seen in the F814W image and in the K band (Broadhurst & Lehár 1995) is not present in the F437M FOC data. The ratio of the flux of the arc to the  $3\sigma$  level of the background noise at the expected position of the counterimage is 250. This limit is 2.5 times greater than the arc-to-counterimage flux ratio ( $\sim 100$ ) in the F814W image (E96).

Our coadded image gives an integrated flux density over the length of the arc of  $1.6 \times 10^{-17}$  ergs  $\text{cm}^{-2}$   $\text{s}^{-1}$   $\text{\AA}^{-1}$ , equivalent to  $B = 21.5$  mag. This is similar to the integrated magnitude obtained by Broadhurst & Lehár (hereafter, F437M and F814W are interchangeably referred to as *B* and *I*-band, respectively).

### 3.2. Astrometry

Astrometry provides critical information needed for mapping the image into the source plane. The task is complicated due to the fact that there is no object other than the arc itself in the FOC field of view. The accuracy of the measurement thus depends upon the knowledge of the distance from the reference object, star A, to the lensing galaxy, and the precision offsetting of *HST*. From the F814W data, Star A was measured to be  $13.19 \pm 0.01$  arcsec west and  $0.99 \pm 0.02$  arcsec north of the lensing galaxy. The errors are due to uncertainties in the correction for geometrical distortion and in the determination of the centroid of star A whose core is saturated in the F814W PC data. Assuming the telescope pointing between the FOC image of star A and the arc is accurately known, our best determination of the relative positions of the arc at F437M and F814W is shown in Fig 1. Relative to the *I*-band arc (in contours), the arc as seen by the FOC data (in grayscale) appears to be shifted radially toward the lensing galaxy. The shift is measured to be  $12 \pm 10 \pm 10$  mas, where the first error is due to correction for geometrical distortion, and the second is due to telescope pointing (R. Jedrzejewski, private communication).

### 3.3. Polarization

Our polarization measurement confirms that *FSC10214+4724* is highly polarized. The integrated linear polarization of the entire arc, determined from the total fluxes measured with each of the three polarizers, is  $31 \pm 3$  percent for the first visit,  $24 \pm 5$  percent for the second and  $26 \pm 5$  percent for the third. The average degree of polarization then is  $28 \pm 3$  percent, consistent with the ground-based observations (G96). The position angles, measured east of north, for the three separate visits appear to be in satisfactory agreement. They are  $59 \pm 3.5$  deg for the first visit,  $61 \pm 7$  deg for the second and  $67 \pm 5$  deg for the third. The overall orientation, after averaging the Stokes parameters from the three visits,

is  $62 \pm 2.7$  deg, compared to the ground-based observations of  $69.9 \pm 0.2$  deg by G96, and  $75 \pm 3$  deg by Lawrence et al. (1993). Lawrence et al. integrated their polarimetry data over the 400 to 1000 nm range. G96 obtained spectropolarimetry over the same spectral range as Lawrence et al., and their position angle appeared to be constant over that range. The discrepancy in the position angles is not understood, but may be due to inclusion of low surface brightness regions in the ground-based data which are not detected by *HST*.

Taking advantage of the unresolved nature of the arc in the transverse direction, a high resolution one-dimensional polarization map was produced by summing over  $10 \times 3$  pixels, in the transverse and tangential directions, respectively. The choice of number of pixels was made so as to improve the signal-to-noise ratio while preserving the structure along the tangential direction. The combination of these pixels gives substantial improvement in signal-to-noise ratio and minimizes the effect of misregistration and differing PSF, thus allowing reliable determination of the polarization for each combined pixel. As shown in Figure 2, the total intensity  $I$ , the degree of polarization  $P$  and the position angles vary significantly along the arc. The maximum change in the position angle,  $\Delta\theta_{max}$ , is  $35 \pm 5$  deg.

#### 4. Discussion

There are no sources other than *FSC10214 + 4724* detected in the FOC field of view, even though the image is very deep, with a  $3\sigma$  point source detection limit of  $B \approx 27.5$  mag in the central  $6 \times 6$  arcsec<sup>2</sup>. This is consistent with the expectation from faint field galaxy source counts (Williams et al. 1996).

#### 4.1. Absence of the counterimage

The absence of the counterimage (component 5 in E96) in the F437M FOC image is surprising. This may be due either to larger lensing magnification in the F437M bandpass than was seen by E96, or to extinction by dust in the lensing galaxy. We address each of these possibilities in turn.

Although gravitational lensing is achromatic, the magnification is a sensitive function of source size and position near the caustic in the source plane. Different distributions for the UV and optical continuum regions can account for the different appearances of *FSC10214 + 4724* at different wavelengths noted by Matthews et al. (1994), as in the case of *K*-band arc. The lens model suggested by E96 and a source geometry as sketched in Figure 3 reproduce qualitatively the inferred lensing magnification of 250, the observed arc morphology and the arc astrometry at F437M. Our source model puts the *B*-band source with a radius of  $\sim 20$  pc, right on the cusp in the caustic line, approximately 100 pc away from the center of the *I*-band source. The fact that the *B*-band source lies on the caustic is not entirely fortuitous but perhaps due to "magnification bias". In reality the scattering clouds may be widely distributed, but only the regions near the cusp are highly magnified and readily detected. Because of uncertainties in telescope pointing, we take the observed difference in angular position of the arc to be an upper limit rather than a detection. However, the small differences in morphology of the arc, when combined with the lens model do indeed suggest a small offset between the *B*-band and *I*-band sources, and hence a small offset between the *B*-band and *I*-band arcs of roughly 10 mas, well within the upper limit provided by the telescope astrometry (section 3.2). For the simple quasar picture in which a scattering cloud is illuminated by a hidden AGN in the source plane, the positional offset of the *B*-band cloud relative to that in the *I*-band suggests that the direction from the hidden AGN to these sources could be different, and perhaps could give rise to different

position angles (since the polarization vector is perpendicular to the direction to the AGN). However, existing spectropolarimetric data indicate that position angle is independent of wavelength (Goodrich, private communication).

If in fact there is no radial shift between the  $I$  and  $B$  band data sets, reddening in the lensing galaxy may still explain the absence of the counterimage at  $B$  band, since the counterimage and the arc are viewed through different parts of the elliptical lensing galaxy, and therefore may be affected by different amounts of extinction. Dusty gravitational lenses are common (e.g., MG 1131+0534 Larkin et al. 1994 and MG 0414+0534 Lawrence et al. 1995). If it is assumed that the arc is not significantly reddened since its optical path is  $\sim 10$  kpc away from the center of the lens galaxy,  $A_V > 0.67$  mag at  $z = 0.9$  is required to produce  $E(B - I) > 1$  mag observed for the counterimage, using the extinction law from Cardelli, Clayton, & Mathis 1989 ( $R_V = A_V/E(B - V) = 3.1$ ). This optical depth is similar to that found in some local elliptical galaxies (Goudfrooij & de Jong 1995). This extinction, if present, would reduce the intrinsic lensing magnification ratio estimated from the F814W data to less than 45, which is closer to the magnification ratio of roughly 30 estimated in the far infrared (E96). The source structure and hence the polarization angle could then be very similar for both F437M and F814W.

#### 4.2. Pattern of Position Angles

Given a lensing magnification, it is possible to infer the source diameter,  $D$ , using the lens model (E96). The observed pattern of position angles then may be directly translated into the source plane, and can be used to infer the location of the dust enshrouded AGN. For the quasar model above, the projected distance,  $R$ , from the continuum region to the hidden AGN may then be estimated by the simple relation,  $D \approx R\Delta\theta_{max}$ , where  $\Delta\theta_{max}$  is the maximum change of the position angle. For a range of lensing magnification of 250

to 45,  $D$  varies from 40 to 100 pc, so  $R$  is less than 160 pc. This small scale is generally inaccessible at these wavelengths for objects at redshifts  $z > 2$ . Notice this range of  $R$  is similar to the distance from the active nucleus to the continuum region found for the local Seyfert 2 galaxy, NGC1068 (Capetti et al. 1995).

The relative position of the source and the caustic is crucial in explaining the many features of the arc. For example, if some part of the source is within the cusp, that part will be triply imaged in the arc such that the parity of the first image is opposite to the parity of the second, and is the same as that of the third. A monotonic position-angle gradient across the triply imaged part of the source will naturally produce the rising, falling and rising position angle pattern shown in Figure 2c.

### 4.3. Future Observations

Either a different  $FSC10214 + 4724$  source geometry in the source plane or extinction in the lensing galaxy could be responsible for the fact that the counterimage is present in the  $I$ -band, WFPC2 data while absent in the  $B$ -band, FOC data. We expect much of this ambiguity to be resolved by a more accurate determination of the relative astrometry of the  $FSC10214 + 4724$  system with planned *HST* WFPC2 observations in the F467M and F814W. In the present study, the morphological differences between the unpolarized  $I$ -band and polarized  $B$ -band images of  $FSC10214 + 4724$  are not large, because the differences in size and location of the regions emitting these components are small relative to the resolution of the high-magnification gravitational lens combined with *HST*. However the same is not expected to hold for the narrow emission line region (the NLR). From detailed studies of AGN at low redshifts, it is known that the NLRs and the extended NLRs can exhibit complex morphologies over hundreds of parsecs to kiloparsec scales (e.g. Pogge 1989, Wilson & Tsvetanov 1994). At high redshifts, the emission-line nebula around

powerful AGN can be quite spectacular, reaching sizes of 10-100 kpc (e.g., McCarthy, Spinrad & van Breugel 1995, Armus et al. 1998). If the NLR of *FSC10214 + 4724* has similar properties, its appearance through filters isolating specific UV and optical emission lines should be quite different from its broad band, continuum morphology. For example, if the NLR is displaced towards the lensing galaxy, the arc will split up into three images and the counterimage will become relatively more prominent. If displaced away, the arc will become shorter and the counterimage will again become relatively more prominent. The displacement, shape and size of the NLR may be determined from the observed morphology and the lens model. This makes *FSC10214 + 4724* a unique system for direct imaging of quasar emission regions at high redshift. Such observations are planned in *HST* cycles 7 and 8 to image this system in narrow-band filters centered on the narrow emission lines, [C IV] $\lambda$ 1549, [Ne V] $\lambda$ 3426 and [O III] $\lambda$ 5007.

## 5. Summary and Conclusions

We have reported imaging polarimetry of the gravitationally-lensed object *FSC10214 + 4724*, carried out with 0.04 arcsec resolution at F437M (roughly *B*-band) using the Faint Object Camera on *HST*. The principal results of this work are the following:

- a. The F437M source appears as an unresolved arc, 0.7 by  $< 0.04$  arcsec, coincident to within the errors with the arc seen at F814W by E96.
- b. The absence of a counterimage suggests that the apparent magnification at F437M is 250, considerably higher than measured at F814W and inferred for the far infrared (E96). It is possible that this effect is due to differential extinction in the lensing galaxy. However, if further work shows that ~~that~~ the magnification is in fact higher at F437M

than at F814W, then the emitting region at the shorter wavelength must be smaller and closer to the caustic of the lensing potential. The size and position difference might be a consequence of patchy UV extinction in the high luminosity core of *FSC10214 + 4724* (Lacey, Rawlings & Serjeant).

c. The net polarization of the arc at F437M is consistent with what has been determined from ground-based measurements, but we determine that the position angle of polarization rotates systematically with position along the arc. The total variation of the angle is about 35 deg. Under the assumption that the polarization is due to scattering of continuum radiation from an embedded source, the projected distance of the scattering region from this source is less than 160 pc; it could be as small as 60 pc if the magnification is in fact as high as 250.

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Fig. 1.— *HST* Faint Object Camera image of *FSC10214+4724* in filter F437M in grayscale. The overlaid contours are from the PC F814W data (E96), with the centroid of the lensing galaxy and counterimage labelled as 2 and 5, respectively. Notice the absence of the lensing galaxy and the counterimage in the F437M FOC data. North is 76.0 deg clockwise from vertical.

Fig. 2.— One dimensional profiles of *FSC10214 + 4724* in filter F437M. Total intensity  $I$  (panel a), Degree of polarization  $P$  (panel b) and position angle  $\theta$  (panel c) vs. position in arcsec along the arc. The smoothing box for the data was 3 pixels parallel to the arc  $\times$  10 pixels transverse to the arc. East is to the right.

Fig. 3.— A source model of *FSC10214 + 4724* for lensing magnification of  $\sim 250$ . Solid lines: Position and size of the source in  $I$  and  $B$  bands. Solid vector is the position angle measured by this work. Dotted vectors are the position angle measured by G96. Broken line: the caustic. Dashed line: the location of hidden AGN inferred from the variation of the position angles of polarization observed along *FSC10214 + 4724* arc. (0,0) is the position of the lensing galaxy in the source plane. North is 37.1 deg counterclockwise from vertical.

FSC10214+4724







