Image Deconvolution of the Radio Ring PKS 1830–211\(^1\).

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ABSTRACT

New high quality Keck and ESO images of PKS 1830–211 are presented. Applying a powerful new deconvolution algorithm to this optical and infrared data, both images of the flat spectrum core of the radio source have been identified. An extended source is also detected in the optical images, consistent with the expected location of the lensing galaxy. The source counterparts are very red at \(I – K \sim 7\), suggesting strong Galactic absorption with additional absorption by the lensing galaxy at \(z = 0.885\), and consistent with the detection of high redshift molecules in the lens.

\(^1\)Based on observations obtained at the ESO La Silla Observatory, Chile and at the W. M. Keck Observatory, Hawaii, which is operated jointly by the California Institute of Technology and the University of California.

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1. Introduction

The bright radio source PKS 1830–211 (Jauncey et al. 1991) has attracted much attention as the most detailed example of a lensed radio ring. Among the classically-lensed QSOs, its short time delay of 44 days (van Ommen et al. 1995) and clean lens geometry (e.g., Subrahmanyan et al. 1990; hereafter S90) make it a good candidate for measuring $H_0$. The lens, a gas rich galaxy at $z=0.89$, was discovered in the millimeter via molecular absorption (Wiklind & Combes 1996), which is seen towards only one of the two flat spectrum hot spots (Wiklind & Combes 1996, Frye et al. 1997). The presence of a nearby M-star as well as heavy extinction along the line of sight ($b=-5.7$ degrees) had until now hampered the identification of the lens and the source. In this paper we describe how the MCS deconvolution algorithm (Magain, Courbin, & Sohy 1997) was used to detect the counterparts of this bright radio ring in deep Keck optical and infrared images.

2. Observations - Reductions

Near IR $J$ ($\lambda_c=1.25$ micron) and $K'$ ($\lambda_c=2.15$ micron) images were obtained on the nights of 1997 April 14 and 15 with the IRAC2b camera on the ESO/MPI 2.2m telescope, which uses a NICMOS3 256×256 HgCdTe array. The good seeing (0″6-0″7) and the fact that a good sampling is desirable for deconvolution, led us to choose the smallest pixel size available on this instrument i.e., 0″151, resulting in a total field of view of 38″ on a side. The data were taken and reduced exactly in the same way as in Courbin, Lidman & Magain (1997), but with a different pixel size. Several standard stars were observed during the night. The standard deviation in the zero points was less than 0.02 magnitudes for both $J$ and $K'$. The IR magnitudes reported in this paper are on the JHK system of Bessell & Brett (1988).

Near-IR Keck $i$ data were obtained on the night of 1994 April 5 with NIRC (Matthews & Soifer, 1994). Five 80 second $K$ images were combined using the sigma clipping algorithm available in IRAF. The pixel size is 0″157, similar to that used with IRAC2b. The images were obtained under marginally non-photometric conditions, with a zero point uncertain by about 0.1 magnitude.

Six dithered $I$-band images were obtained during the full moon night of 1997 June 15 using the Keck $\Pi$ telescope and LRIS (Oke et al. 1995). The CCD detector was a Tektronix 2048×2048 with a pixel size of 0″215. The individual exposure times were restricted to 3 minutes in order
to avoid saturation of the brightest stars in this extremely crowded field. The background was very high. The images were bias subtracted and flat fielded in the standard way. All of them have a seeing close to 0′.8. No standard star was observed, but a flux calibration could be performed relative to an I-band image taken at La Silla with the 0.9m telescope on the night of 1997 April 15.

3. Deconvolution

The MCS deconvolution code (Magain, Courbin & Sohy, 1997) was applied to all the images. Due to the low signal-to-noise and the numerous bad pixels in single IR images, these were medianed in groups of 9 dithered and sky subtracted frames. The resulting images have better signal-to-noise and cosmetics. Two infrared-bright nearby stars, although outside the field of view, produced scattered light in the field, forcing us to reject a fair fraction (∼40 percent) of our observations in the $K'$ band. One of the culprits was the known source IRAS 18306-2106. Two stacks were obtained in $J$ (total exposure time of 1920 sec) and four in $K'$ (total exposure time of 1440 sec). Only one such stack was obtained for the IR Keck images since we had only 5 dithered frames to combine.

We chose a pixel scale in the deconvolved images that is a factor of two smaller than the pixel scale in the original data, to insure that the sampling theorem is satisfied in the deconvolved images. After deconvolution, the resolution is 2 pixels Full-Width-Half-Maximum (FWHM) for all data. The corresponding final pixel scales and resolutions on the plane of the sky are given in Fig. 1.

We constructed the infrared Point-Spread-Function (PSF) from the relatively isolated, bright star labelled H in Djorgovski et al. (1992; hereafter D92). In the optical images, the stars mentioned in D92 are all saturated. Consequently the PSF was constructed from 4 fainter stars about 30″ away from the radio ring. Crowding in the optical field made the the quality of the PSF rather poor, especially in the outer wings of the hexagonal Keck PSF, introducing systematic residuals into the deconvolved image.

The deconvolution process is described in detail by Courbin, Lidman & Magain (1997) and was applied to the present data in an identical manner. As output from the procedure one gets a deconvolved image decomposed into point sources and a diffuse background which is compatible with all the input images included in the data set. The photometry and the astrometry of the point sources are also obtained as byproducts of the deconvolution (see Tables 1 and 2). Objects near the frame edges are not well-fitted. (e.g., objects labelled 2, 3 and 4 in Fig. 1). Note that object 1 is never well-fitted by a point source and leaves significant residuals after deconvolution. We therefore conclude that it is extended or that it is a very strong blend of point sources.
4. Results and discussion

In Fig. 1 we present both the raw and deconvolved images in $I$, $K'$ and $K$. The resolution of the deconvolved images is $\sim 0''.15-0''.20$. The deconvolved images clearly show one red point source at the position expected for the NE radio source of PKS 1830–211. Another red object is observed close to the position of the SW radio source of the lensed system, but the extended nature of the source and the poor quality of the PSF do not allow to sort out its detailed morphology. The photometry and astrometry of the field are presented in Tables 1 and 2 and Fig. 2. For the near-IR observations, we performed the deconvolutions several times with different initial conditions. The error bars are the $1\sigma$ dispersions between the different results. In the optical, the deconvolution program was run using 5 different PSFs in order to quantify the additional errors introduced by a poor knowledge of the PSF.

The red star in D92 dominates the total flux in the I-band, while in the infrared the component near the NE radio source takes over. With our high signal-to-noise we can show that its shape is compatible with a point source, and its color, $I - K = 6.9$, is much redder than any “normal” star (e.g., Koornneef, 1983). The $I$, $K'$, and $K$ positions are all within the $1\sigma$ radio error bars. In Fig. 2 we all objects are aligned with respect to the M-star so that we can compare the different positions measured for the NE and SW components at optical and IR wavelengths.

Molecular absorption towards the two lensed images was spatially resolved in the mm, and the separation between the lensed images was found to be $0''.98$ (Frye, et al. 1997). In our optical and IR images the SW component is $0.61 \pm 0.13''$ and $0.85 \pm 0.09''$ respectively, away from the NE component. A plausible explanation for the apparent positional shift between the optical, IR and radio positions is that the SW component is a blend of two objects: the lensing galaxy and the heavily reddened SW component seen in the radio images.

The flux ratio between the two lensed images of the source is $0.973 \pm 0.016$ at radio wavelength (S90), and about $18.2$ in $K$ ($3.15\pm0.2$ magnitudes). The combination of a reddened SW radio source plus blue lens can explain the large flux ratios. Both NE and SW components are reddened, making PKS 1830–211 another good example of a dusty lens, along with MG 0414+0534 (e.g., Annis & Lupino 1993) and MG1131+0456 (Larkin et al. 1994), the mean galactic extinction being far below the values obtained for PKS 1830–211. At the lens redshift, the observed $K$-band corresponds to a central wavelength of $1.17\,\mu$ in the restframe. For the galactic reddening curve, the extinction in this band is $A_{(1.2\mu)} = 0.37A_V$ (Sandage & Mathis, 1981). Thus, the differential extinction is about $8.5$ magnitudes in the $V$-band and implies $E(B-V) = 2.75 \pm 0.2$, in good agreement with the value of $2.4$ derived from recent HST NICMOS3 observations (e.g., Kochanek et al. 1998).

If the total extinction is comparable to the differential extinction between the two images, then the source is attenuated in the observed $K$-band by about $3$ magnitudes. On the other hand, considering simple SIS or point-mass models, the magnification by the lens may be similar, or somewhat less, let say $2$ magnitudes. So, a reasonable value for the unobscured un-lensed $K$-
magnitude of the source may be around 14. A typical quasar has $V - K \sim 3$. So the unobscured, $V$ magnitude of the source may be about 17, which is bright, but not unreasonable for $z \sim 1 - 2$.

5. Conclusion

The main result of our study is the detection of the optical and near-IR counterpart to the NE radio source of PKS 1830-211 and the possible detection of the SW component and lensing galaxy. However, our SW component candidate might be the lensing galaxy alone (its position is also in good agreement with the predictions from the models calculated by S90 and Nair, Narasimha & Rao, 1993) or, given the crowding in the field, a red galactic object almost coincident with the position of the SW radio source. The hypothesis of a demagnified third image of the source (S90) between the 2 main lensed images is unlikely as in such a case extinction of the lens would have made it visible in the IR. Furthermore, the IR centroid of the SW component would have been shifted towards “object E” rather than towards the radio position of the SW component.

The higher contrast between the NE component and nearby M-star in the infrared make near-IR spectroscopy necessary for finding the source redshift. Deep, high resolution near-IR imaging is needed to reveal the exact nature of the faint SW component. However, even at the highest resolution attainable, 0".2- 0".3 in the IR with HST (in particular in $K$ where the SW component of PKS1830-211 is best visible), deconvolution will be essential to discriminate between the SW component candidate, the lensing galaxy and additional faint galactic stars.

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REFERENCES


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Fig. 1.— [Top left] Field of 4.0′′ around PKS 1830–211 observed with Keck II in the $I$-band. This image is a stack of 6 frames with a pixel size of 0.215′′ and seeing of 0.8′′. [Top middle] Mean of 4 temporary stacks (see text) obtained in the $K'$ band with the ESO/MPI 2.2m telescope. The pixel size 0.151′′ and the seeing is 0.7′′. [Top right] Mean of 5 $K$-band images obtained with Keck I and NIRC. The pixel size is 0.157′′ and the seeing is 0.7′′. Bottom row, from left to right: [Bottom left] Simultaneous deconvolution of the 6 $I$-band frames: resolution of 0.215′′ and pixel size of 0.1075′′. [Bottom middle] Simultaneous deconvolution of the 4 $K'$ images: final resolution of 0.151′′ and pixel size of 0.075′′. [Bottom right] Deconvolution of the mean of 5 NIRC images: resolution of 0.157′′ and pixel size of 0.0785′′. In all the images North is up, East to the left. The M-star, the NE QSO component candidate and the blended SW component + lensing galaxy candidate are indicated. The scale is given in arcseconds relative to the M-star. The NE QSO image is directly south of the M-star.
Fig. 2.— Positions observed for the different objects detected in the optical and near-IR along with their 1σ error bars, relative to the M star. The large open circles are radio positions whose radius corresponds to the error bars quoted by S90. The black dots show the positions measured from the near-IR images while the open circles show the result obtained from the $I$-band data.
Table 1: Summary of the photometry.

<table>
<thead>
<tr>
<th></th>
<th>M-star</th>
<th>NE Comp.</th>
<th>SW Comp.+Lens</th>
<th>Limiting Mag.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I(\text{Keck})$</td>
<td>$19.3 \pm 0.1$</td>
<td>$22.0 \pm 0.2$</td>
<td>$22.3 \pm 0.3$</td>
<td>$24.0$</td>
</tr>
<tr>
<td>$J(\text{ESO})$</td>
<td>$18.1 \pm 0.1$</td>
<td>$18.7 \pm 0.3$</td>
<td>$&gt; 20.5$</td>
<td>$20.5$</td>
</tr>
<tr>
<td>$K'(\text{ESO})$</td>
<td>$17.3 \pm 0.3$</td>
<td>$15.8 \pm 0.2$</td>
<td>$19.0 \pm 0.4$</td>
<td>$19.1$</td>
</tr>
<tr>
<td>$K(\text{Keck})$</td>
<td>$16.6 \pm 0.2$</td>
<td>$15.1 \pm 0.1$</td>
<td>$18.2 \pm 0.2$</td>
<td>$21.3$</td>
</tr>
</tbody>
</table>

Note. — Results are given for the M-Star, the NE component, and the SW component of the lensed source plus lensing galaxy. The limiting magnitude for each of the bands is given in the final column.

Table 2: Summary of the astrometry

<table>
<thead>
<tr>
<th></th>
<th>NE Comp.</th>
<th>SW Comp.+Lens</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x(I)$</td>
<td>$+0.08 \pm 0.01$</td>
<td>$+0.48 \pm 0.1$</td>
</tr>
<tr>
<td>$y(I)$</td>
<td>$-0.70 \pm 0.01$</td>
<td>$-1.15 \pm 0.1$</td>
</tr>
<tr>
<td>$x(J)$</td>
<td>$-0.07 \pm 0.01$</td>
<td>$-$</td>
</tr>
<tr>
<td>$y(J)$</td>
<td>$+0.54 \pm 0.01$</td>
<td>$-$</td>
</tr>
<tr>
<td>$x(K')$</td>
<td>$+0.06 \pm 0.01$</td>
<td>$+0.54 \pm 0.07$</td>
</tr>
<tr>
<td>$y(K')$</td>
<td>$-0.52 \pm 0.01$</td>
<td>$-1.16 \pm 0.07$</td>
</tr>
<tr>
<td>$x(K)$</td>
<td>$+0.06 \pm 0.01$</td>
<td>$+0.59 \pm 0.05$</td>
</tr>
<tr>
<td>$y(K)$</td>
<td>$-0.54 \pm 0.01$</td>
<td>$-1.20 \pm 0.05$</td>
</tr>
</tbody>
</table>

Note. — Results for the NE and SW components of the lensed source plus lensing galaxy are given in arcseconds, relative to the M-star, together with their $1\sigma$ error bars.