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ADAPTIVE OPTICS IMAGING OF QUASAR HOSTS

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RESUMEN

Presentamos los resultados de imágenes en las bandas H y K con óptica adaptativa (OA) usando el sistema PUEO en el CFHT, de doce cuásares ($z < 0.6$). El quasar mismo ($m_V > 15.0$) es utilizado como referencia para la corrección. Las imágenes, obtenidas en pobres condiciones de seeing, tienen resoluciones espaciales típicas de $FWHM \sim 0.3$ segundos de arco antes de la deconvolución. La imagen deconvolucionada de PG 1700+514 tiene una resolución espacial de 0.16 segundos y revela con todo detalle tanto la galaxia albergadora como la compañera. La comparación entre las imágenes *HST* y CFHT de PG 1700+514 muetra cuán poderosa puede ser la OA, tanto más utilizada en telescopios de la clase de 10 m. Cuatro de los doce objetos presentan compañeros y signos obvios de interacción. Las imágenes 2D de tres de ellos indican claramente la presencia de barras y brazos espirales. La morfología del resto es difícil de determinar a partir del perfil de brillo; se necesitan imágenes más profundas, que podrán obtenerse con OA en telescopios de la clase de 10 m. El análisis de imágenes simuladas muestra que galaxias inicialmente elípticas siempre se reconocen como tales, mientras que las galaxias de disco pueden ser identificadas como elípticas para longitudes de escala del disco pequeñas y para contribuciones importantes del QSO.

ABSTRACT

We present the results of adaptive optics (OA) imaging of twelve ($z < 0.6$) quasars in the H and K bands using the PUEO system mounted on the Canada–France–Hawaii Telescope (CFHT). The QSOs ($m_V > 15.0$) themselves are used as reference for the correction. The images, obtained under poor seeing conditions, have typical spatial resolution of $FWHM \sim 0.3$ arcsec before deconvolution. The deconvolved H band image of PG 1700+514 has a spatial resolution of 0.16 arcsec and reveals a wealth of details on the companion and the host galaxy. Comparison between the *Hubble Space Telescope* and CFHT images of PG 1700+514 shows how powerful and competitive ground-based AO can be. Close companions and obvious signs of interactions are found in four of the twelve objects. The 2D images of three of the host galaxies unambiguously reveal bars and spiral arms. The morphology of the other host galaxies are difficult to determine from 1D surface brightness profiles, and deeper images are needed, which could be obtained with AO systems on 10 m class telescopes. Analysis of mock data shows that elliptical galaxies are always recognized as such, whereas disk hosts can be missed for small disk scale lengths and large QSO contributions.

Key Words: **GALAXIES: QUASARS – GALAXIES : FUNDAMENTAL PARAMETERS — GALAXIES : PHOTOMETRY**

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1. INTRODUCTION

Evidence that nearby bright galaxies contain massive dark objects in their center has become increasingly compelling over the last few years, and early suggestions that a tight correlation exists between the mass of the dark object and the mass of the bulge (Kormendy & Richstone 1995) have been convincingly corroborated (Magorrian et al. 1998; Ferrarese & Merrit 2000). It is thus possible that AGN activity is a usual episode in the history of most, if not all, present-day bright galaxies. One way to investigate this is to determine the luminosity and morphology of galaxies hosting quasars. In addition, this gives clues on the range of conditions needed for strong nuclear activity to occur.

Several studies of quasar host-galaxies have been performed with the main aim of distinguishing between radio-loud and radio-quiet quasars, either from IR ground-based observations (Dunlop et al. 1993; McLeod & Rieke 1995; Taylor et al. 1996) or by using *Hubble Space Telescope* (*HST*) imaging (Disney et al. 1995; Bahcall et al. 1997; McLure et al. 1999; Kirkhakos et al. 1999). The detection and analysis of host galaxies is difficult even from space (Bahcall et al. 1994; Bahcall et al. 1995; McLeod & Rieke 1995; McLeod & McLeod 2001). Indeed, the determination of the point spread function (PSF) and the subtraction of the point source image are crucial in this work. Differentiation between the two classical profiles, either an exponential disk or a de Vaucouleur power law, is effective only in the regions close to the center, or in the far-wings of the PSF (see figure 1 of McLure et al. 2000). Because of seeing limitation, PSF subtraction is the main limitation in determining host galaxy morphologies from the ground. With the advent of adaptive optics, however, it is possible to alleviate this limitation (Stockton et al. 1998; Aretxaga et al. 1998; Hutchings et al. 1999; Márquez et al. 2001). In addition, observing in the infrared minimizes the difference in luminosity between the host and nucleus, again improving our ability to determine the host morphology. PSF determination is still a major problem, but the difficulties are balanced by the prospect of using 10 m class telescopes, which will provide higher sensitivity and better spatial resolution.

In this contribution we present the summary of the results of a pilot program aimed at testing the capabilities of adaptive optics in this field. The details can be found in Márquez et al. (2001).

2. SAMPLE SELECTION AND DATA

In order to use adaptive optics correction, quasars were selected such that the nuclei are bright enough to be used as the wavefront reference point source. The sample of radio-quiet quasars were all PG type with $m_b < 16.5$ and with redshift less than 0.6. The radio-loud objects were selected from 3C, 4C, B2 and PKS catalogues with the same magnitude and z criteria. The final objects observed (see Table 1 in Márquez et al. 2001) were selected based upon the suitability for the observing conditions during the observing runs.

We used adaptive optics bonnette (PUEO) and the IR camera KIR on the CFHT in 1998 May and 1999 May. The weather conditions were poor during both runs and the FWHM of the seeing PSF was never better than 0.8 arcsec. The adaptive optics correction was performed on the QSOs themselves. The final images after the usual process of NIR imaging reduction have a typical resolution of $FWHM \sim 0.3$ arcsec. After each science observation an image of a star with similar magnitude ato that of the QSO was taken in order to determine the PSF for deconvolving the images. Because of rapid variations in the weather conditions, however, it was not always possible to follow this predefined procedure.

A synthetic PSF function, derived from the stellar images, was used to deconvolve each of the images. As it was not always possible to apply a standard procedure because of fluctuating seeing conditions, a careful although somewhat arbitrary, choice of the PSF had to be made. In Márquez et al. (2001) we have shown that the best PSF to be used for deconvolution is that obtained using the star with the FWHM closest to that of the science exposure. In general, this illustrates the crucial role played by a careful PSF determination in AO observations.

3. ANALYSIS

In each of the images, we first masked out the companion objects and the ghosts arising from the telescope optics. We then obtained the surface brightness profiles of the galaxies using the IRAF [1] task ELLIPSE. The resulting profiles were fitted over the radius range from 3 times the FWHM of the PSF up to the point where the galaxy surface brightness level falls below 2σ of the background level. We have systematically fitted an exponential disk and a de Vaucouleurs $r^{1/4}$ law. Of the ten objects for which we can extract some morphological information, two of the host galaxies are most probably barred spirals, the rest being ellipticals or very early-type spirals. We note that in general the number of points we can use to fit either profile is not large enough to unambiguously distinguish between the two fitted profiles. At small radii, the excess of light between the observed profile and the model disk could be caused by the presence of a bulge. The morphology is determined considering both the 2D luminosity spatial distribution and the 1D profile. It is apparent that to discriminate between both morphologies the S/N ratio must be high at large radii.

The magnitudes of the hosts have been derived by integrating the $r^{1/4}$ profiles for all the objects. Indeed, it can be seen that there is an excess of light

[1] IRAF is the Image Analysis and Reduction Facility made available to the astronomical community by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy (AURA), Inc., under contract with the U.S. National Science Foundation.

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at small radii compared to the disk profile for all objects. This suggests that in our sample, the disk galaxies also have a strong bulge and/or a strong bar. This is confirmed by the 2D luminosity distribution. We have also subtracted a scaled version of the most suitable PSF for each nucleus, imposing a non-negative profile in the center (see Márquez et al. 1999). The resulting host magnitudes, computed by integrating the PSF-subtracted images, are in good agreement with those obtained from the profile fitting.

The results of the analysis are given in Table 2 in Márquez et al. (2001). We also give the number of objects (probably companions) found within 5 and 10 arcsec from the quasar down to $m_H = 20.5$ and the maximum radial distance (in arcsec and kpc) to which the host is detected at a significance level of 3σ above the background.

We concentrate on the results for PG 1700+514. The description of the remaining objects can be found in Márquez et al. (2001).

4. PG1700+514

PG 1700+514 is one of the most IR-luminous, radio-quiet BAL quasar (Turnshek et al. 1985; Turnshek et al. 1997). Ground-based imaging revealed an extension about 2 arcsec northeast of the quasar (Stickel et al. 1995), which was shown by adaptive optics imaging and follow-up spectroscopy to be a companion with a redshift of 140 km s^{-1} blueward of the quasar (Stockton et al. 1998). NICMOS observations led Hines et al. (1999) to argue that the companion is a collisionally induced ring galaxy. The fit to the spectral energy distribution (SED) and the Keck spectrum of the companion imply that the light is emitted by an old population of stars plus an 85 Myr-old starburst (Canalizo & Stockton 1997). Note however that the H band flux ($m_H \sim 16.6$) deduced from *HST* imaging is much larger than that predicted by the model. Stockton et al. (1998) showed that the inclusion of embedded dust can produce a SED consistent with both the optical spectrophotometry and the IR photometry.

The image obtained at CFHT is shown in Figure 1. We confirm the findings by Stockton et al. (1998) that the companion has the appearance of an arc with several condensations. We used different PSFs to deconvolve the image. The best deconvolution is obtained using the star with the FWHM closest to that of the AGN (0.30 arcsec). The image has a final resolution of 0.16 arcsec and is probably the best image yet obtained of this object. The companion is seen as a highly disturbed system with a

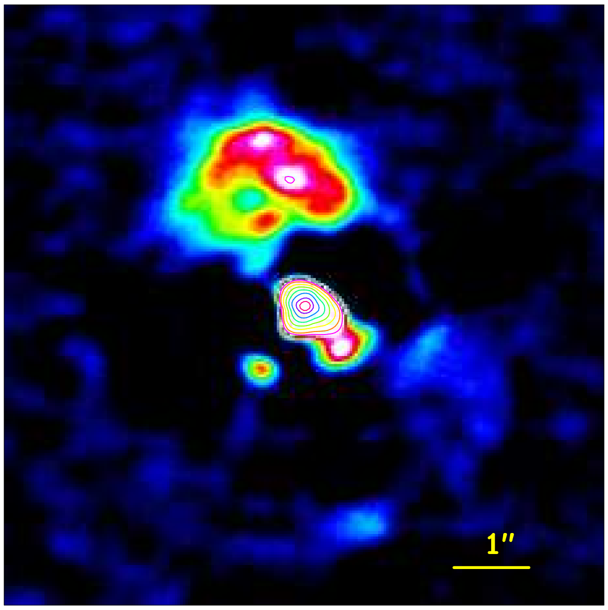

Fig. 1. Image of PG 1700+514 after deconvolution using the PSF given by the star with the PSF closest to that of the quasar. The resulting image has a final resolution of $FWHM = 0.16$ arcsec.

bright nucleus and a ringlike structure; the nucleus being decentered with respect to the ring. The host galaxy is clearly seen around the quasar with a bright extension to the southwest, first noted by Stickel et al. (1995) and clearly visible in the optical images by (Stockton et al. 1998). In addition, we detect a bright knot to the southeast which is not seen in the NICMOS data probably because of the presence of residuals in the PSF subtraction. Comparison between the *HST* and CFHT images of PG 1700+514 shows how powerful AO can be, and bodes well for the use of the technique on 10 m-class telescopes. No obvious relation is found between the near-IR image and the radio map (Hutchings et al. 1992).

5. MOCK DATA

We have fitted the 1D profiles of the host galaxies with either exponential or de Vaucouleurs laws. In order to test our fitting procedure, we have generated images of model elliptical and disk galaxies with scale lengths and effective surface brightness within the range derived from the data. The same orientation and axis ratio is given to all of them. A point source is added in the center of the galaxy to mimic the quasar. An appropriate amount of noise is added, and then the images are convolved with a typical observed PSF. The mock images are analyzed in the same way as real data.

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We first note that an elliptical galaxy is always recognized as such by the fitting procedure, whereas a disk galaxy is better fitted by an $r^{1/4}$ law when the unresolved point source contributes more than half the total light. This means that, at least with data of similar quality to those presented here, the fraction of elliptical galaxies in the sample may be overpredicted. Going deeper, by at least 0.5 to 1 magnitude, should help solve this problem as it is apparent that the distinction between spiral and elliptical profiles is easier when the galaxy is detected at larger distances from the central point source.

It is interesting to note that the output magnitudes are brighter than the input in both cases, elliptical or disk galaxies. The reason for this is probably the difficulty in determining the extension of the PSF wings which, if not subtracted properly, will artificially increase the flux of the host galaxy. In the case of spirals, the difference is as large as 0.6 mag when the contribution of the point source is the same as the contribution of the host galaxy. For the ellipticals, the difference is less but still important when the QSO dominates the total flux.

Note that the ratio between the QSO and the host galaxy luminosities is expected to increase with redshift. The above bias tends to imply that host galaxy luminosities could be overestimated.

6. CONCLUSIONS

AO imaging in the H and K bands has been used to study the morphology of QSO host galaxies at low and intermediate redshifts ($z < 0.6$). We detect the host galaxies in eleven out of twelve quasars (five radio-quiet and seven radio-loud). The images, obtained under poor seeing conditions, and with the QSOs themselves as reference for the correction, have typical spatial resolution of $FWHM \sim 0.3$ arcsec before deconvolution. Close companions and obvious signs of interactions are found in four objects. The 2D images of three of the host galaxies unambiguously reveal bars and spiral arms. For the other objects, it is difficult to determine the host galaxy morphology on the basis of one-dimensional surface brightness fits alone. In the best case, the deconvolved H band image of PG 1700+514 (with a spatial resolution of 0.16 arcsec) reveals a wealth of detail on the companion and the host galaxy, and is probably the best-quality image of this object thus far.

We have simulated mock images of host galaxies, both spirals and ellipticals, and applied the same analysis as to the data. Disk hosts can be missed for small disk scale lengths and large QSO contributions. In this case, the host galaxy can be misidentified as an elliptical galaxy. Elliptical galaxies are always recognized as such, but with a luminosity which can be overestimated by up to 0.5 mag. The reason for this is that the method used here tends to attribute some of the QSO light to the host. This is also the case for disk galaxies with a strong contribution of the unresolved component.

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