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HIGH-RESOLUTION OPTICAL IMAGING OF THREE QSOs

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ABSTRACT

Using a rapid guiding camera on the Canada-France-Hawaii telescope, *R*-band images have been obtained of three low-redshift QSOs with FWHM close to 0.5 arc sec. The QSOs are a radio-loud, a strong IR source, and a BAL, respectively. In all cases, features are seen close to the nucleus which are unusual and indicate that a statistical multicolor study at this resolution will produce significant new information on QSO environments and evolution.

Key words: quasars–*R*-band images

1. Introduction and Data

Most of what is known of the immediate environment of QSOs has been derived from high-resolution optical imaging. At 1.5 to 2.0 arc sec resolution it is possible to determine that most low-redshift QSOs ($z < 0.5$) are extended, but very little can be learned of their structure, colors, and peculiarities. A factor of two increase in resolution (available at a few excellent sites and telescopes) allows the host galaxy sizes, shapes, and colors to be measured as well as some marked peculiarities, such as tidal disturbances, extra nuclei, and companion objects. It becomes marginally possible to measure the luminosity profile for an azimuthally averaged image. From the best QSO images (0.7–0.8 arc sec resolution) and observations of lower redshift related objects, it is clear that in general the host galaxies and environs of QSOs are complex and disturbed. Many (and possibly all) are in tidal interaction with a companion galaxy, are tidally distorted, and contain areas of hot star formation and heavy dust obscuration; all of which cause severe confusion in a poorly resolved image. In addition, there may be features which relate directly to the active nucleus, such as jets or regions illuminated by the nuclear power source. These have only marginally been seen in the best images to date. A detailed and proper understanding of the QSO phenomenon, its evolution, and its powering requires a significant sample of images with a further increase in resolution of a factor of two or more. Higher resolution allows the proper study of galactic scale features, which are of order 0.5 arc sec and less at redshifts to 0.5. It also reduces the severe scattered light contamination and CCD saturation of the inner regions (often the most significant in terms of these studies) of the host galaxy, by the brilliant nuclear radiation.

For these reasons we have performed initial observations of selected QSOs with the CFHT high-resolution camera (McClure *et al.* 1989; Racine and McClure 1989). Two half-nights were allocated to this initial investigation, and, unfortunately, most of this time was lost to poor weather. In the few hours of clear weather the uncorrected seeing was not exceptional (0.7 to 1.2 arc sec). Only three QSOs were observed, selected as objects of known individual interest. The results were very encouraging: The images obtained have resolution close to 0.5 arc sec and in all cases contained significant new information dependent on the high resolution. A further advance was that the QSO nuclei themselves were used as the guide objects, ensuring optimum operation of the fast guiding optics and also conveniently reducing the signal (and scattering) at the nucleus by a factor of about 20. (This reduction is due to the fact that most of the guide-star light is transmitted through a hole in the coating of one of the camera mirrors. Only ~5% is reflected onto the CCD by the glass surface of the mirror blank.)

The observations were obtained on 1989 June 1 with an *R*-band filter, as shown in Table 1. The objects observed were selected for position in the sky and brightness of their nuclei. Two objects had previously been observed with the CFHT with 0.4 arc sec pixels and ~1.0 arc sec seeing and were known to have interesting structure and other properties. The third was chosen for its other properties but had no earlier observations by us.

The sky was not photometric; the telescope full aperture was used, with the fast guiding mirror operating, but not the "smart shutter". Individual exposure times varied from 600 to 1200 sec. The instrument was adjusted to place the guide star as near as possible to the center of the small (1.5 arc sec) guide aperture. The QSO nucleus in all

*Guest Observer, Canada-France-Hawaii telescope, which is operated by the National Research Council of Canada, the CNRS of France, and the University of Hawaii.

TABLE 1

R-Band Imaging 1989 June 1

Name	m_v	z	air mass	exposure (secs)	FWHM (arcsec)
1223+252	16	0.27	1.01	1200	0.42 x 0.55
1334+246	15:	0.32	1.04	1800	0.49 x 0.56
1411+442	14.9	0.09	1.16	1875	0.52 x 0.66

three cases was bright enough to be used as the guide star. In order to use the 5% transmitted signal from the nucleus, a dome flat was used with the same mirror adjustment. The detector is the CFHT RCA4 1024 × 640 pixel CCD, which yielded a pixel size of 0.11 arc sec on the sky. The exposure times were not long enough to study the faintest structure, but good signal was obtained on the bright inner parts of the QSO galaxies. The data were processed using DAO VISTA in the normal way.

In our diagrams (Figs. 1–3) the central isophotes include the imperfectly restored central image seen through the 1.5 arc sec guiding hole. The innermost contours do show the shape of the point-spread function for the image, and we measure an ellipse of diameters ~0.5 × ~0.6 arc sec for the FWHM (see Table 1). This may be due to a slight astigmatism in the images formed by the telescope primary mirror.

The new images do not reach as faint as the older ones, as the smaller pixel sizes on the sky would require about four times the exposure to reach the same faint limit. Due to the constraints of time and weather, the present exposures limit us to studying the bright inner structure of the QSO.

2. 1223+252

This is a radio-loud QSO whose previous images are shown and described in Hutchings (1987) and Hutchings, Johnson, and Pyke (1988). The QSO has an irregular elliptical shape and appears to be interacting with a fainter irregular companion 8 arc sec away. The radio structure was observed by Gower and Hutchings (1984) and consists of a weak core and two FR II lobes each some 30 arc sec to the NE and SW. The radio and optical structure do not appear to be related in size or orientation.

Figure 1 shows the new *R*-band image. We note that the shape of the host galaxy resembles an inclined two-armed spiral. However, the outer parts of the arms are brighter than the inner, and the W arm is considerably brighter, with a lower luminosity area nearer to the nucleus. This may be an area of reddening, as seen prominently in the inner regions of IRAS objects, but we lack the *B* image to measure this. (The older *B* and *R* images show that the outer arms are red, although the details are not resolved.) Subtraction of an elliptical model from the image reveals that there are probably N and S arms as well, comparable with the E arm in luminosity, but less obvious as they are seen in projection closer to the center of the galaxy. The new data are not deep enough to detect the connecting luminosity, seen clearly in the lower-resolution *B* and *R* images.

There is an inner bright feature to the SW of the nucleus which may be on the inner W arm or may be a separate entity. We note that this object, ~1 arc sec from the nucleus, lies on the radio axis and may be related to the radio energy transfer from the nucleus. It lies in the direction of the nearer and fainter radio lobe.

The new image is remarkable in that it reveals clearly spiral structure in a radio QSO. (The radio structure is unusual in having a weak core.) It also reveals an inner feature which may be related to the radio emission. Color imaging of this object will allow us to determine whether there is significant dust or young star-formation in the galaxy. The large size and faint core of the radio structure suggest that the source is moderately old (10^7 yrs), so that the hottest stars in an initial starburst will have evolved by now.

3. 1334+246

This QSO was discovered as an IRAS source (see Low *et al.* 1989). The IR color and luminosity are typical of an IRAS QSO, and the optical luminosity is lower, consistent with the usual heavy reddening of these objects (Hutchings and Neff 1988; Sanders *et al.* 1988). B. Wills (private communication) reports that the optical light is highly polarized. We have no previous imaging data on the object. It is radio quiet.

The *R*-band image reveals a large elongated object with a slight S symmetry which could indicate an inclined spiral. It is less clumpy than 1223+252, and there is a

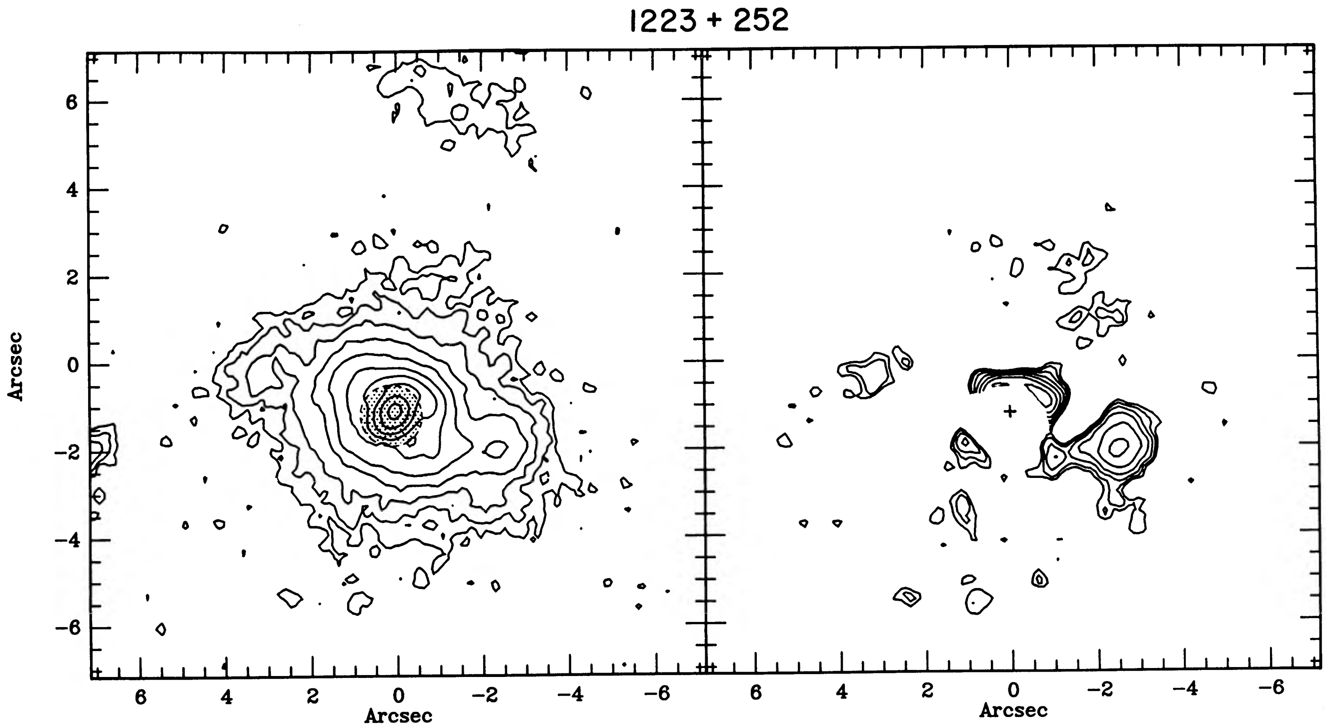

FIG. 1–*Left:* Contours of *R*-band image of radio-loud QSO 1223+252, on a log scale a factor 1.8 apart. N is up and E is to the left. This should be compared with the images in Hutchings *et al.* (1988). The circle at the nucleus shows the guiding hole, and the contour irregularities across this are not real. *Right:* Image after removal of smooth elliptical model. Note several broken spiral features, the bright SW arm, and the bright spot 1 arc sec from the nucleus to the SE.

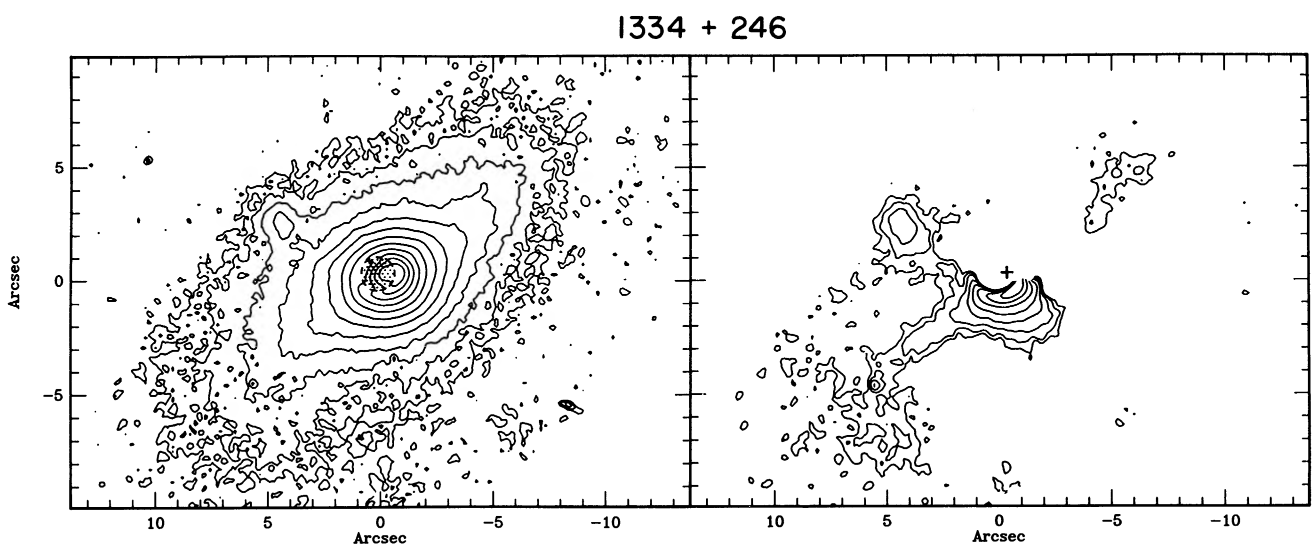

FIG. 2–*R*-band image of IRAS QSO 1334+246 and residual from smooth elliptical model as in Figure 1. Note the NE blob and connecting filament, straight jet to SE and outer bend, bulge of light opposite the blob, and faint curved NW filament.

bright elliptical central bulge. There is also an extended object 5 arc sec off the short axis with a fainter jetlike extension curved toward but not into the nucleus. Except for the effect of the guiding hole, there is no sharp structure close to the nucleus. Subtraction of a smooth elliptical model shows the curved jetlike feature clearly. It also shows a remarkable linear feature from the nucleus along the main optical axis, which curves sharply in the outer regions of the galaxy. A similar feature on the other side is much fainter, does not reach the nucleus, and is curved. Here, too, color information would indicate how much of the apparent structure is due to reddening within the galaxy. Finally, there is a broad area of excess luminosity extending 3 arc sec from the nucleus opposite the jet.

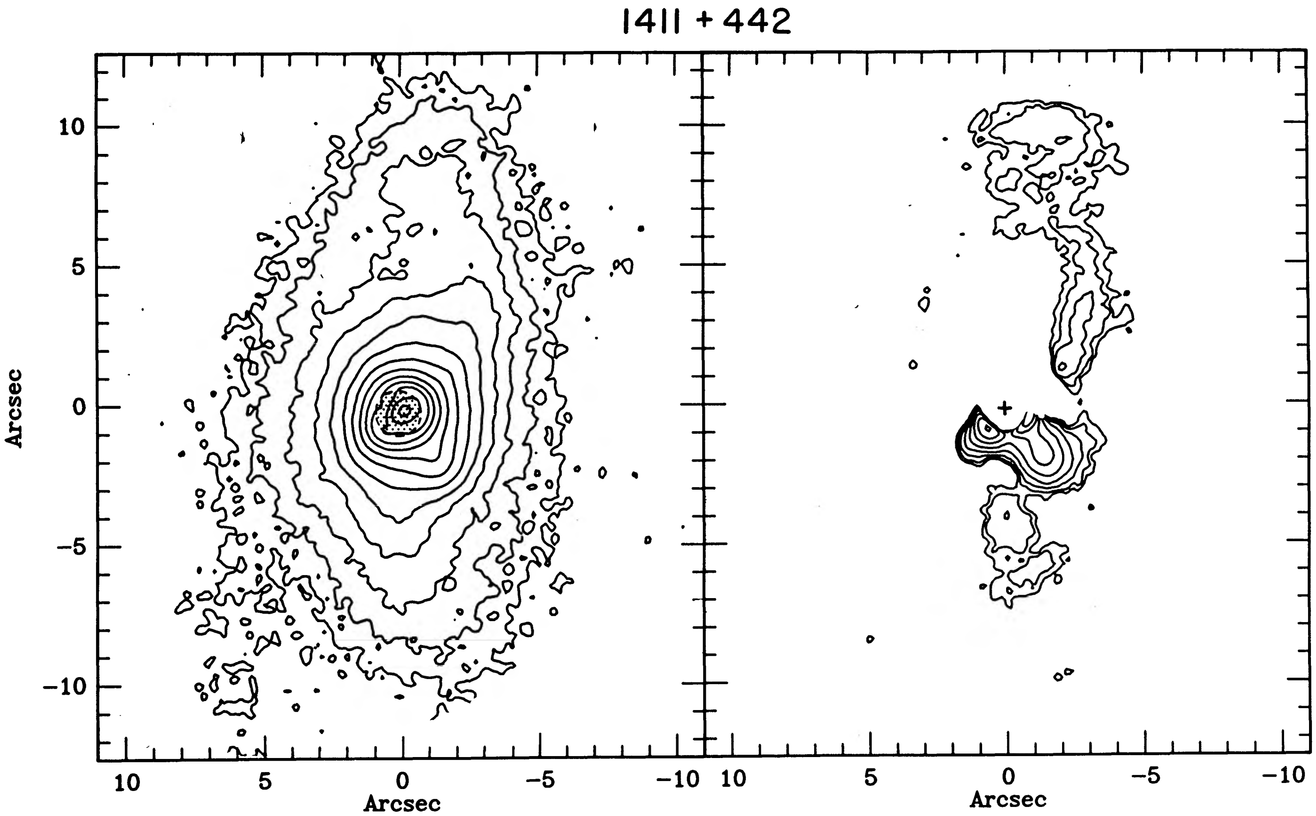

FIG. 3–Inner part of BAL QSO 1411+442. Note the strong linear feature near to (but separate from) the nucleus to the SW and the irregular brightness of the inner arms. The blue jet to the SE and the large outer arm can just be seen (see Malkan *et al.* (1987) for larger scale and fainter features).

Intensity profiles show that the long axis scale length is large (15 Kpc). The azimuthally averaged profile is exponential beyond 5 arc sec radius, and the $R^{1/4}$ plot shows a poor fit. The size of the galaxy is large: at least 24 arc sec, or 75 Kpc.

This object is remarkable in the smoothness of its general morphology and the superposed faint jetlike structures to the NE and SE. It appears to be a recently disturbed galaxy with little preexisting structure (E or S0?). The nature of the disturbance appears to be the tidal interaction of the small object to the NE and consequent warping of the main galaxy. We have no direct clue as to the polarization: Color imaging would indicate whether the nucleus is obscured by dust and seen in scattered light. The IR luminosity and optical morphology suggest it is a relatively new QSO. Most of the structures seen here would not be detectable with 1 arc sec or worse images, and this is another example of the need for high resolution in a proper study of the evolution of QSO episodes in galaxies.

4. 1411+442

This QSO is in the Palomar BQS (Schmidt and Green 1983) and is also the lowest redshift BAL QSO (Malkan, Green, and Hutchings 1987). Malkan *et al.* published CFHT broad- and intermediate-band images with resolution somewhat over 1 arc sec. In those images the QSO is seen to lie in an inclined spiral galaxy with one very extended arm culminating in a broad red blob. A blue linear jetlike feature extends from the nucleus across the inner part of this arm. The whole galaxy lies in a faint halo off center from the nucleus. The galaxy is not sufficiently edge-on for the BAL spectrum to arise in the plane of the spiral. It is a weak unresolved radio source.

The new data have very weak signal on the outer arm and its structure but are well exposed in the nuclear region and in the inner two symmetrical arms. These arms show smooth curvature, but subtraction of a smooth model shows that they are clumpy as in 1223+252, possibly due to reddening. The blue jet seen in the early data is barely detectable in the new R-band image but is seen to curve toward the nucleus in the inner 4 arc sec.

The most interesting feature seen in the new data is a bright linear feature extending 2.5 arc sec to the S of the nucleus. This short narrow feature is not resolved in the earlier data and is not connected with the spiral structure seen further away. It is approximately at right angles to the larger "blue" jet and is many times brighter. The interpretation of this extraordinary feature is not clear, nor is its connection, if any, with the BAL properties of the nucleus. More observations in *B* and at line wavelengths would be very useful in defining its properties more clearly. Although it lies as close as 1.6 Kpc from the nucleus it does not appear to extend closer, unless its inner parts are heavily reddened.

5. Discussion

We have obtained detailed and significant images of sub-arc-second structure in all three of the objects observed. In two cases these structures were not visible in data with resolution ~1.0 arc sec. This suggests strongly that this technique will enable significant new analysis of the structure of QSO host galaxies, particularly in their inner brighter regions, which are hidden by scattered nuclear light in conventional observations. With the present small sample and the lack of color and emission-line information, it is premature to attempt an analysis. While it is clear that HST will provide yet higher resolution, it will be limited by small pixel sizes to even smaller brighter regions and by the lack of large amounts of observing time. Observation of a significant sample of QSOs at 0.5 arc sec or better from the ground clearly offers an important complement to HST and a major new database in understanding QSO activation and evolution.

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