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Adaptive optics observations of ultra–luminous infrared galaxies I. J, H, K images of Mkn 231*

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Abstract. We present adaptive optics observations in J, H and K of the Ultra–Luminous Infrared Galaxy, Markarian 231. This galaxy is the one among ULIRGs that shows most clearly the character of a QSO with a very peaked nuclear source. Even with a FWHM PSF of 0.11 arcsec, our images show that the central source is still unresolved and should be more compact than 50 pc; in addition, the position on the [J-H]/[H-K] color-diagram of this point-like source is very close to the locus of QSOs. Both results point to an actual AGN – almost unreddened – at the center of Mkn 231. The underlying extended emission appears to be extremely red in a circum-nuclear region of ≈ 2.5 kpc, that should be identified with the hot molecular gas disk recently found in H_2. In addition, we detect on the deconvolved images a second source (B) at 0.15 arcsec north to the nucleus with [H-K] colors that are consistent either with the stellar nucleus of a merging galaxy, or with a giant HII complex of violent star formation. We favor the later interpretation since this source lies in the direction where the molecular hydrogen emission peaks.

Key words: adaptive optics – infrared: galaxies – – galaxies: starburst – galaxies: Seyfert – galaxies: individual: Mkn 231

1. Introduction

The activity in the nucleus of active galaxies is generally divided in two distinct categories: on the one hand, it involves phenomena of a characteristic size of 0.01 to a few parsecs, associated with a true Active Galactic Nucleus (AGN, i.e. QSO, Seyfert), most probably due to a super-massive black hole accreting the surrounding gas. On the other hand, enhanced star formation activity (starburst) may take place in a characteristic size of a few hundreds of parsecs. Several reasons lead one to believe that there is a link between these two types of activity: *i)* a large number of galaxies show these two phenomena simultaneously (e.g. NGC 1068 or NGC 7469); *ii)* the correlation between a Seyfert nucleus starburst activity increases with IRAS luminosity (Sanders, 1992); *iii)* the very high concentration of gas in the heart of galaxies exhibiting either one or the other type of activity (e.g. Planesas et al., 1991); *iv)* the strong correlation between both types of activities and the interaction (or merging) with a neighboring galaxy (Clements et al., 1996).

Do Ultra Luminous Infrared Galaxies (ULIRG $\equiv L_{IR} > 10^{12}$ $L_\odot$) represent an extreme case of such a link as proposed by Sanders et al. (1988)? Relying on similar properties of infrared QSOs and ULIRGs, those authors suggest that ULIRGs would be progenitors of quasars and, for most of them, should host an enshrouded AGN that is the primary source of the enormous energy released by those objects. On the other hand, most of the observable phenomena in ULIRG are tracers of a burst of star formation. Determining if the main source of energy in ULIRG is a hidden AGN or a compact huge starburst is a key question which is still a matter of debate ten years after the proposal by Sanders et al.. For instance, the high angular resolution radio interferometric measurements of Condon et al. (1991) lead to the conclusion that a resolved source, and thus a compact starburst claimed the authors, was detected in all ULIRG, but one – Mkn 231, precisely –; however, since such resolved sources are also detected in genuine QSO which are almost certainly powered by an unresolved central engine, the question still deserves attention. Recent ISO results (Lutz et al., 1996) also pointed to a starburst origin of the primary energy source of ULIRGs, but the observed sample remains modest. Among the tests, an important one is to try to resolve the source, because if an AGN is actually dominating the dust heating, then the core should be unresolved in practice (at a distance of 100 Mpc, the FWHM at 2.2 μm of the thermal emission by a dust envelope around a 10^{12} $L_\odot$ source would have a size less than 100 micro-arcsec).

The near–infrared range is especially well suited to such high angular resolution studies since: a) that's where the best resolution can be reached; b) it is possible to probe rather deeply through the presumably very opaque dust; c) most of the sources of radiation (stellar photosphere, nebular emission of ionized gas, heated dust, AGN) do emit in this range, generally with characteristic color indices. We have started a program of broad-band and line imaging of several ULIRGs, using *PUEO*, the new Adaptive Optics system recently installed at CFHT (Véran

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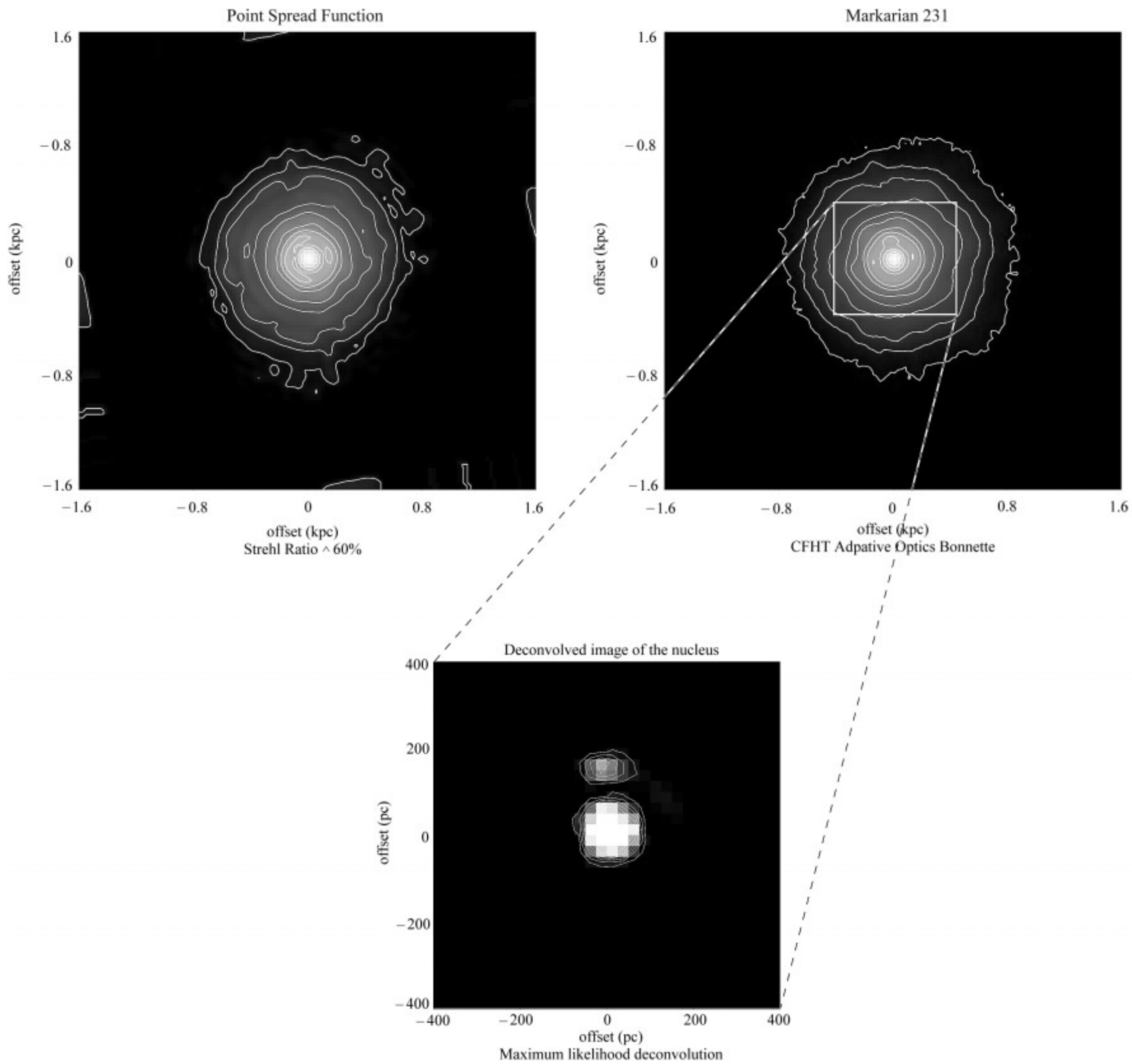

Fig. 1. Upper–left: grey-scale image superimposed on contours of the PSF obtained from the WFS data, in square–root scale. Field is 4.3”×4.3”. Upper–right: Markarian 231, K band, same scale. Lower: an enlargement of a one arc-second square of the deconvolved image using the maximum likelihood method (linear scale). For all images North is up and East at left

et al., 1997). This paper is the first of a series presenting and discussing the results of this program.

1.1. Mkn 231

According to Sanders et al. (1987), this is the brightest infrared galaxy in the local universe (z$<$ 0.1), with an infrared luminosity $L_{IR} = 3 \times 10^{12}\,\mathrm{L}_\odot$ (Soifer et al., 1987). It is clearly the result of an advanced merger, as shown by visible image taken by Sanders et al. (1987): two tails are apparent on the east side of the galaxy, aligned along on north/south axis. In the following, a distance of 160 Mpc will be used. Mkr 231 is an interesting object, because its true nature has been eluding us for many years. As a matter of fact, Markarian 231 has many similarities to a true active nucleus: it has many radio features of a Seyfert 1, such as its spectrum, its compactness (Neff & Ulvestad, 1988), its variability and its polarization (Goodrich & Miller, 1994). Even more so, its variability and its optical spectrum (absorption lines, broad optical/near-infrared lines) are fairly characteristic of a quasar (Hamilton & Keel, 1987). Yet its luminosity in X-rays is lower than that of a true Seyfert 1 and would be closer to that of a Seyfert 2 (Heisler & Vader, 1994), unless it is a buried or a X-ray quiet QSO. The later interpretation is favored by Krabbe et al. (1997) who derived a maximum extinction A_V=6.6 from H_α/P_α. Very high resolution images obtained with VLBI (at 18 cm) show a single source that is unresolved, even at a scale of 0.02” (17 pc on the galaxy), although there is an extension nearly along a north/south axis, 30 pc long (0.036”). All these results point to a true active nucleus. On the other hand, several indices reveal a central star-forming region: the unpolarized ultraviolet spectrum and strong Fe II emission lines (Lipari, Colina & Machetto, 1994), the detection of an OH megamaser (Baan, 1985) and more recently the detection, through near-IR H_2 lines, of an extended circum-nuclear structure (2.4 kpc in diameter) of hot molecular gas (Krabbe et al., 1997): one third of the IR luminosity could then be ac-

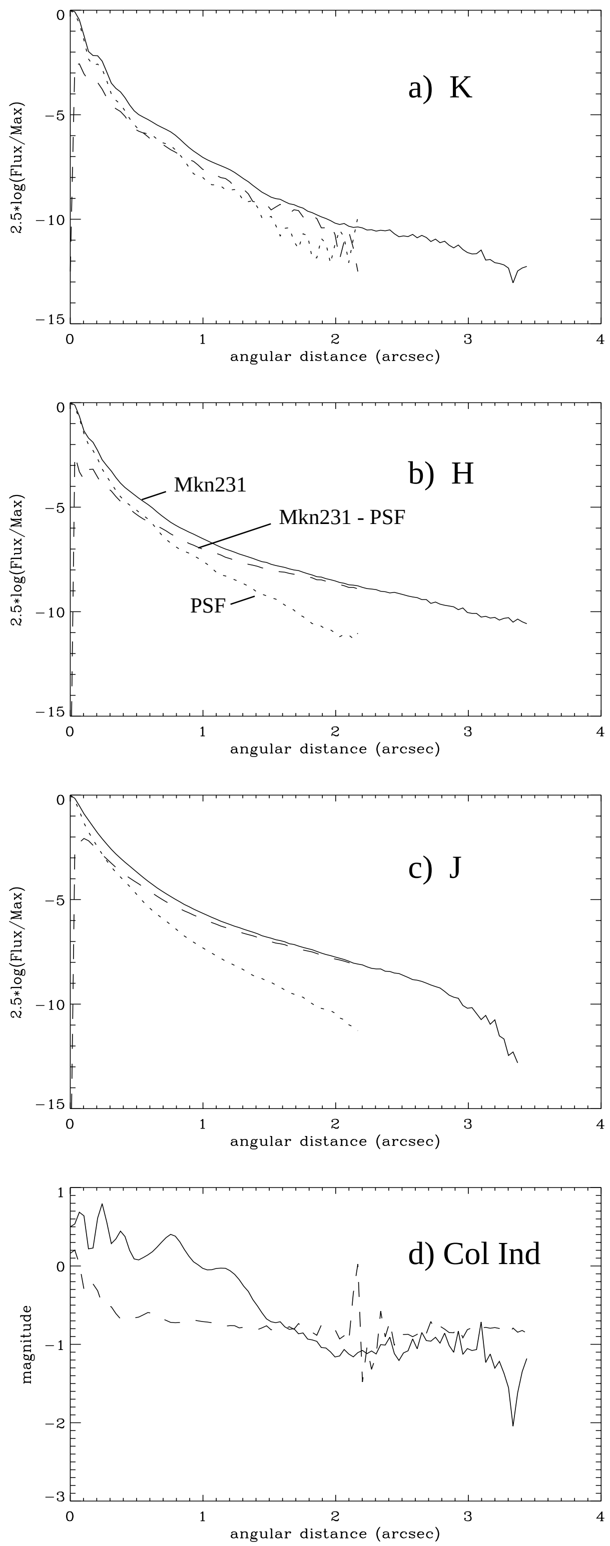

Fig. 2. a Average radial brightness profiles in K band of the PSF, of the nuclear region of Mkn231 and of their difference; all profiles – in log scale – are centered on the the brightest pixel and all fluxes are normalized to this brightest pixel; note that the log of the difference is $-\infty$ at this point. Solid line: Mkn231; dotted line: PSF; dashed line: difference. **b** Same as **a** in H band. **c** Same as **a** in J band. **d** Radial variation of the colors of the extended emission, i.e. differences between the dashed curves in **a**, **b** and **c**; solid: [H-K]), dotted: [J-H].

counted for by the star-forming region which would likely be associated to the hot molecular component.

2. Observations

The observations were carried out using adaptive optics. This is a technique that attempts to restore the image quality to what it was prior to being degraded by atmospheric turbulence. This is achieved by correcting wavefront errors in real time with a deformable mirror and a wavefront sensor.

PUEO, the CFHT's adaptive optics bonnette is a curvature based (Roddier et al., 1991) system, with a user–friendly interface (Arsenault et al., 1994; Véran et al., 1996). In brief, the instrument is installed at the Cassegrain focus of the CFH 3.6 m telescope and includes a 19 electrodes bimorph mirror coupled to a curvature wavefront sensor. The Monica infrared camera, a facility instrument of the University of Montreal (Nadeau al.1994), was mounted at the f/20 focus, with a plate scale of 0.034"/pixel (to properly sample diffraction limited images down to J band); it features a 256^2 Nicmos–3 array and the field is therefore fairly small (8.7"$\times$8.7"), but sufficient to cover the region of interest in the case of Mkn 231.

Markarian 231 was observed on June 22^{nd} 1996. As the nucleus is bright and point-like in the visible (m_V = 13.6) it was possible to use it as the reference source for wavefront sensing. Because of the bright Seyfert-like nucleus, the elementary integration time was short (1, 5 and 20 s in respectively K, H and J bands), but co-addition of 60 frames lead to a good signal to noise ratio. A photometric standard (FS 24) was observed before the observations. For deconvolution purposes, a PSF was derived from the wavefront sensor measurements, following a new method developed by Véran et al. (1997): this PSF has the important advantage to be fully representative of the actual seeing conditions of the observation since it is deduced from data synchronously recorded with the IR images. Thanks to the good seeing quality (0.60 arcsec), a fairly good correction of the turbulence was possible and Strehl ratios of 57%, 31% and 13% in K, H and J bands respectively, were obtained.

Six different locations, with relative offset of $\approx$ 0.8 arcsec, were measured in order to improve the flat-fielding and reduce the effect of bad pixels. Centering of the different exposures was done through cross-correlation techniques; the sky level between the different overlapping regions was adjusted to reach an homogeneous background, while for co-addition of the overlapping regions, rejection of the deviating pixels (clipped mean) was done.

The rest of image processing is fairly standard: bad pixel correction, sky and dark current subtraction, flat–field division (flat-field measurement was performed on the dome). The more advanced processing of deconvolution (Maximization of likelihood) was also applied to each set of images, using the synthesized PSF.

3. Results

The achieved resolutions are 0.13", 0.11" and 0.11" in K, H and J bands respectively. We note that in J band, the image is

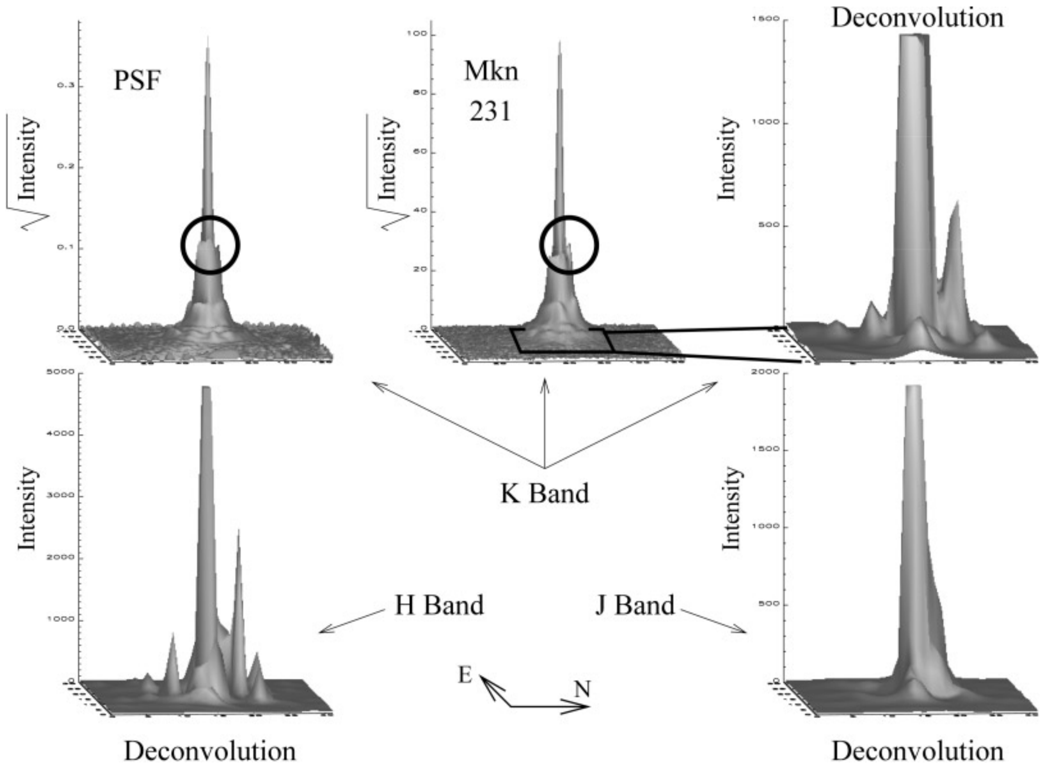

Fig. 3. Top left and center panels: 3-D representation of the PSF and Mkn 231 K-band images (square root scale); the first Airy disk is encircled. Other panels: comparison of the 3–D representation of the deconvolved images in J, H and K (linear scale, and clipped data): at all wavelengths, a faint northern extension is seen. Orientation is indicated by arrows at bottom.

no longer diffraction limited and deconvolution cannot be as effective because some of the higher frequencies are dominated by noise.

Our observations show that the image is almost totally dominated by a quasi-point-like nucleus at all wavelengths (see Fig. 1 for the K image), and, for instance, the Airy rings are well apparent (encircled region on Fig. 3). With a FWHM of 0.11–0.13"., this implies that this source is significantly smaller than 50 pc. If we compare the radial profile to the Point Spread Function, we find however that there is indeed an extended faint emission that becomes more and important relative to the usings of the point-like nuclear source at increasing radial distances. This extended halo appears clearly on Fig. 2-a, -b and -c, where the average radial profiles in J, H and K have been plotted respectively for Mkn231, the PSF and their difference. The derived colors of the point source are [J-H] = 0.99 and [H-K] = 1.12; they are significantly bluer than the colors measured in an aperture of 2.5 arcsec centered on the nucleus: ([J-H] = 1.34 and [H-K] = 1.37: (Carico et al., 1990): this means that the extended halo is intrinsically much redder than the nucleus itself.

On the bottom panel (d) of Fig. 2 we have also plotted the [H-K] and [J-H] radial color variations: this plot clearly reveals that there is a rapid change in [H-K] color at $\theta \approx 1.3$ arcsec from the nucleus, at which location the emission becomes bluer, the variation reaching 1.3 magnitude at 2 arcsec from the nucleus. We propose to relate this sudden change in near-IR colors to the detection by Krabbe et al. of a strong concentration of hot molecular gas in a region of 2.4 kpc in diameter, which is fully consistent with the size of 2.2 kpc (2.7 arcsec) that we derive from the FWHM of the [H-K] central peak of Fig. 2-d). Whether this very red color is due to a strong extinction of a starburst emitting region (hot dust + nebular emission from HII regions + photospheric emission) or to an excess in the K band due to the contribution of H_2 lines is not clear.

In order to look for fainter structures, and since a fair estimation of the PSF is available, we have applied the maximum likelihood deconvolution method (Lucy-Richardson) to our images.

Deconvolution allows to probe the fainter levels, down to a contrast of $10^{-3} \sim 10^{-4}$. The most striking feature on the deconvolved image is a single spike at north, especially prominent on the K frame (Fig. 1 and Fig. 3). In the following we will call this spike source B. Since, on the K image, its location is on the first diffraction ring, one can be suspicious at first glance. However, several indicators point to a physical origin of that spike:

- First of all, the contrast of the spike (peak value normalized to peak of the unresolved nuclear source) on the K band image is about 6×10^{-3}, that is fairly high compared to usual deconvolution artifacts.
- It also appears in H band with an even better contrast (3×10^{-2}), *at the same place*, i.e. no longer on the first Airy ring in H-band.
- The J band image (Fig. 3) shows a slight elongation of the object in the same direction as the spike appears (nearly to

the north). This is probably the most convincing piece of evidence because if the object is unresolved, it cannot be a deconvolution artifact.
- If this structure was due to a change in the static PSF, or some fixed aberration (that would then appear in all bands), it is difficult to conceive what kind of aberration could produce such a high frequency detail. Furthermore it would probably not appear as an elongation of the PSF if it was not diffraction limited.
- Finally, the orientation of this structure is well aligned with the elongation observed at different wavelength as discussed in the next section.

Because non-linear deconvolution methods as Lucy do not keep the total flux constant, even a rough evaluation of the photometry of the secondary source by classical aperture photometry or even PSF fitting would be doubtful; we have preferred a comparison method where we simulate a twin of the source by adding to the original image a weighted PSF at a same radial distance, but at a symmetric position with respect to the nucleus. By properly adjusting the weight, we can obtain a deconvolved image on which the two secondary sources (actual and synthetic ones) are of same intensity: we assume then that the weighted PSF provides a fair evaluation of the photometry of the secondary source. This is illustrated on Fig. 4 where N-S cuts through the nucleus and nucleus + synthetic source are compared for different locations of the pseudo-source in H and K. Note that the deconvolution in J is not as efficient and we did not try to apply this procedure at this wavelength. The ranges of weights of the PSF (normalized on the maximum at the nucleus) giving best fits are 1.8 – 2.8 10^{-2} in K and 2.8 – 3.8 10^{-2} in H, depending on the location of the source that we allowed to be either at 0.14 or 0.17 arcsec from the nucleus. The corresponding range of the derived [H-K] index for source B is then 0.3 to 1.1.

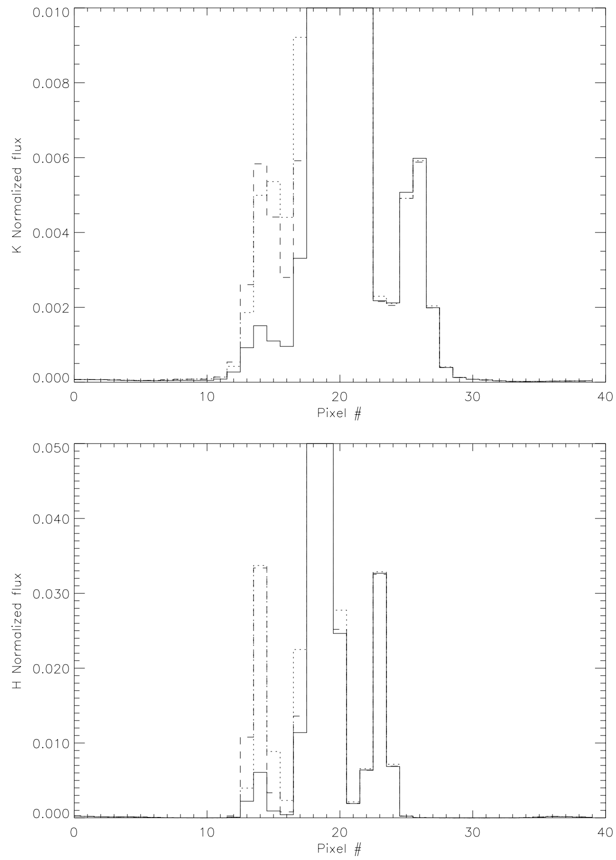

Fig. 4. N-S cut across the deconvolved images of the nucleus at H (upper panel) and K (lower panel); solid line: original image; dotted and dashed lines: same, but a point source (weighted PSF), has been added southward on the original image, prior to deconvolution, in order to simulate a twin of the northern source; two cases have been simulated: the extra source is either at 0.14 arcsec (dots) or at 0.17 arcsec (dashes), as explained in the text.

4. Discussion

4.1. Nature of the bright point source

The near-infrared color indices of the very nucleus are characteristic of a power law $F_\nu \propto \nu^n$ with $n = -2$, which corresponds very well to the location on the [J-H]/[H-K] diagram where most of the QSOs are found. On the other hand, we know that the center of Mkn 231 suffers from a very strong extinction (e.g. Roche, Aitken & Whitmore, 1983), and $A_V = 12$ would be sufficient to bring the color indices characteristic of ionized gas ([J-H]$\simeq$0.1 and [H-K]$\simeq$0.6) to the location where the point source lies on the diagram. However, the measurement of IR lines ratio by Krabbe et al. (1997) tend to prove that the very nucleus is practically not hidden in the near infrared (A_V = 2 – 4.6). This conclusion is consistent with the CO measurement of Bryant & Scoville (1996) who suggest that the molecular gas is concentrated in a thin disk with 60^o of inclination on the line of sight. Our measurements on the central source, which give only an upper limit on its size and color indices representative of a QSO, are additional indication that this source could indeed be an un-obscured AGN at the very center of Mkn231.

However, we cannot exclude that this source is a powerful starburst. In that case, the major fraction of the input stellar luminosity must come from this small region and the power density would be larger than $4.6\ 10^7\ L_\odot pc^{-3}$. This is a large value compared for instance to 30 Doradus/R136, the brightest star forming region in the local cluster, which exhibits a typical energy density of $1.6\ 10^6\ L_\odot pc^{-3}$ (Malumuth & Heap, 1994); however, this is not an unrealistic one if we now compare it to the brightest "super star clusters" in M 82 (O'Connell et al., 1995) or NGC 1569 (O'Connell, Gallagher & Hunter, 1994) that should have luminosity per unit volume in the range $2-4\ 10^7\ L_\odot pc^{-3}$.

4.2. Nature of the secondary source

If, as we think, source B is not a deconvolution artifact, then the two most likely hypothesis about the nature of the companion source are: a) the – stellar – nucleus of a merging galaxy, b) a very dense starburst close ($\approx$ 120 pc) to the Seyfert nucleus.

Is it possible to discriminate between those two interpretations on the sole basis of the colors we derived? The previous estimation of [H-K] in the range (0.3 – 1.1) cannot lead to a firm conclusion, because either cases are possible: if [H-K]= 0.3 then the colors are consistent with a standard slightly reddened stellar nucleus, while the value [H-K] = 1.1 is compatible with nebular emission from giant HII regions reddened by 12 mag of visual extinction (e.g. Fig. 4b of Smith et al., 1995). However, one fact is in favor of the case where the source would rather be a giant complex of star formation: there is a clear tendency for the source to show up at larger distances from the nucleus when wavelength increases (the fit is better with a source at 0.14 arcsec in H and at 0.17 arcsec in K): this would happen if the source is extended and the dust, less opaque at K than at H, let us see a larger extension.

Finally, we want to stress that the location of source B at North, is precisely in the direction where Krabbe et al. (1997) found a conspicuous extended structure of hot molecular gas (see their Fig. 5b), and also where there is an extension of the compact radio source (Neff & Ulvestad, 1988) that may correspond to the non-thermal emission from SN remnants associated to the starburst region.

5. Conclusion

We have presented adaptive optics observations in J, H and K of the Ultra–Luminous Infrared Galaxy, Markarian 231. This galaxy is the one among ULIRGs that shows the character of a QSO with a very peaked nuclear source. Our images with FWHM PSF of 0.11 arcsec show that the central source is still unresolved and should be more compact than 50 pc. The position on the [J-H]/[H-K] color-diagram of this point source is very close to the locus of QSOs. Both results point to an actual AGN, almost unreddened, at the center of Mkn 231. The underlying extended emission appears to be extremely red in a circum-nuclear region of $\approx$ 2.5 kpc, that should be identified with the hot molecular gas disk recently found in H_2 by Krabbe et al (1997). A second important result is the detection, on the deconvolved images in the three bands, of a second source (B) at 0.15 arcsec north to the nucleus with [H-K] colors that are consistent either with the stellar nucleus of a merging galaxy, or with a giant HII complex of violent star formation. We favor the later interpretation since this source lies in the direction where the molecular hydrogen emission peaks.

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