ABSTRACT

We present an $L$-band spectrum of the ultraluminous infrared galaxy IRAS 19254$-$7245 (the Superantennae), obtained with the Infrared Spectrometer and Array Camera on the Very Large Telescope. The high signal-to-noise ratio allows us to study the main spectral features with unprecedented detail for an extragalactic source. We argue that the main energy source in the IR is an obscured active galactic nucleus. This is indicated by the low equivalent width of the 3.3 $\mu$m polycyclic aromatic hydrocarbon feature, the broad absorption feature at 3.4 $\mu$m, and the steep continuum at $\lambda > 3.7$ $\mu$m ($f_\lambda \propto \lambda^{-2.7}$). The substructure of the 3.4 $\mu$m absorption feature indicates that the absorption is due to hydrocarbon chains of six to seven carbon atoms.

Subject heading: galaxies: active — galaxies: individual (IRAS 19254$-$7245) — infrared: galaxies

On-line material: color figures

1. INTRODUCTION

Ultraluminous infrared galaxies (ULIRGs; $L_{\text{IR}} > 10^{12} L_{\odot}$) have been extensively studied at all wavelengths from the radio to the hard X-rays, in order to unveil the energy source—starburst or active galactic nucleus (AGN)—responsible for the huge infrared luminosity. Determining the role of AGNs in ULIRGs is fundamental for evaluating the contribution of accretion to the infrared background and for having a complete view of the population of AGNs in the near universe.

Several diagnostics have been proposed for this purpose. In the optical, the presence of high-ionization narrow emission lines is an indication of the presence of an AGN. However, it is difficult to estimate the contribution of the AGN to the total luminosity just from the optical emission lines. Hard X-rays are in principle a powerful tool. The ratio between X-ray and IR emission in starburst-dominated ULIRGs is expected to be less than $10^{-4}$, and the ratio is $10^{-3}$ to $10^{-4}$ in AGN-dominated ULIRGs (Risaliti et al. 2000). However, if the AGN is covered by a column density $N_H > 10^{23}$ cm$^{-2}$, the presence of the AGN and its total luminosity are hard to determine. In general, all these methods are useful when they can directly measure the AGN luminosity, but they fail in determining whether an AGN is present or not in case of a nondetection.

Mid-infrared spectroscopy provides a powerful way to disentangle the starburst and AGN contribution. Genzel et al. (1998) used the polycyclic aromatic hydrocarbon (PAH) molecules’ emission lines as an indicator of starburst activity in Infrared Space Observatory (ISO) spectra of the brightest ULIRGs. Since PAH molecules are destroyed by the X-ray radiation emitted by AGNs, a high equivalent width (EW) of PAH lines is an indicator of the absence of a strong AGN. Genzel et al. (1998) used the EW of the PAH emission feature at $\lambda \approx 7.7$ $\mu$m as the main diagnostic and concluded that most ULIRGs are dominated by starbursts. Recently, Imanishi & Dudley (2000) showed that ground-based telescopes can provide similarly good—or probably better—data for this kind of diagnostic. In particular, $L$-band spectroscopy of low-redshift ULIRGs allowed us to directly measure the 3.3 $\mu$m PAH feature (which is an indicator of starburst activity similar to the 7.7 $\mu$m feature) and the carbonaceous dust absorption dip at $\lambda \approx 3.4$ $\mu$m (an indication of an absorbed point source like an AGN). Most importantly, the $L$ band is wide enough for a correct estimate of the continuum level; this estimate is needed to measure both the equivalent width of the PAH feature and the detection of the carbon dip. In this way, Imanishi, Dudley, & Maloney (2001) and Imanishi & Maloney (2003) clearly discovered signatures of an AGN dominating the energy output in UGC 5101, which was previously classified as starburst-dominated using ISO spectra only.

The ULIRG IRAS 19254$-$7245 (the Superantennae; Mirabel, Lutz, & Maza 1991) is optically classified as a Seyfert 2. ISO mid-infrared spectroscopy indicates the presence of an AGN in IRAS 19254$-$7245, but it does not provide a clear indication of which is the dominant energy source, the EW of the 7.7 $\mu$m PAH feature being intermediate between typical AGN and typical starburst values (Genzel et al. 1998). Recently, Charmandaris et al. (2002) classified the source as AGN-dominated, based on the same ISO data.

$XMM$-Newton data in the 2–10 keV band suggests that IRAS 19254$-$7245 is AGN-dominated (Braito et al. 2003). The X-ray spectrum suggests that the source is Compton-thick; i.e., the absorbing column density is higher than $10^{24}$ cm$^{-2}$. The total luminosity of the AGN is estimated to be of the order of or higher than $10^{44}$ ergs s$^{-1}$. Berta et al. (2003) fitted the spectral energy distribution of IRAS 19254$-$7245 from the $U$ band to the millimeter band with a starburst+AGN model, estimating a contribution of the AGN to the bolometric luminosity of 40%–50%.

Here we present an $L$-band spectrum of IRAS 19254$-$7245, obtained with the Infrared Spectrometer and Array Camera (ISAAC) on the Very Large Telescope (VLT) as part of a minisurvey of bright ULIRGs. Thanks to the superb quality of both the telescope and the instrument, this is probably the best $L$-band spectrum of a ULIRG ever published and shows the
potentiality of ground-based L-band spectroscopy in the study of active and star-forming galaxies.

2. DATA REDUCTION AND ANALYSIS

IRAS 19254–7245 is a system consisting of two colliding spiral galaxies, at \( z = 0.062 \). The separation of the two nuclei is 8.5 (\( \sim 10 \) kpc). The southern galaxy is classified as a Seyfert 2 (Mirabel et al. 1991), and the northern galaxy shows an optical spectrum typical of starbursts (Colina, Lipari, & Maccarone 1991). At 2 \( \mu \)m, the southern galaxy is brighter by \( \sim 1 \) mag than the northern galaxy (Duc, Mirabel, & Maza 1997). Images at 10 \( \mu \)m show that the mid-IR emission is concentrated in the nuclei, and the southern one is more than \( \sim 5 \) times brighter than the northern one. Finally, ISOCAM observations (Charmandaris et al. 2002) show that more than 90% of the 5–20 \( \mu \)m emission is due to the southern source.

We performed two observations of IRAS 19254–7245 with ISAAC-VLT, on 2002 June 2 and 3. Each observation was 1 hr long. The two nights were photometric, and the seeing was around 1\". In the image acquired before the spectroscopic observation, we detected the two nuclei, and we oriented the 1\" slit in order to obtain spectra of both. However, the northern nucleus turned out to be too faint to obtain a useful spectrum. Therefore, we will not discuss it further.

The spectroscopic observations have been performed in “chopping” mode, with single exposures of 0.56 s. The data were merged, flat-fielded, and sky-subtracted using standard procedures in the IRAF package. A spectrum of the spectro-photometric standard star HIP 183 (B4 III, \( L = 5.5, T_{\text{eff}} = 15,800 \) K) was acquired in the same way for both observations, and was used to obtain the instrumental response, in order to correct the source spectrum.

Since the calibration lamp lines were too faint to be useful, the wavelength calibration was performed using the nominal instrumental range and the wavelength of the carbon absorption features (as described in the next section). Throughout this Letter, we always refer to rest-frame wavelengths, unless otherwise stated.

The absolute flux calibration has been obtained by analyzing the profile of the star along the slit and by estimating the fraction of flux inside the slit, assuming a perfect centering. We estimate that this procedure has an error of the order of 10%. We checked that the two final spectra were consistent, and we finally merged the results of the two observations. The final spectrum, rebinned by a factor of 5, is shown in Figure 1. The error bars are estimated from the Poissonian noise in the sky counts (which are by far the dominant source of noise).

3. DISCUSSION

Previous optical and infrared observations indicated the presence of an AGN in the nucleus of IRAS 19254–7245, but the relative importance of the AGN and starburst components was not clear: the 7.7 \( \mu \)m PAH feature detected by ISO (Genzel et al. 1998) has an intermediate strength (\( S = 0.8 \), where \( S \) is the ratio between the peak 7.7 \( \mu \)m flux and the continuum at the same wavelength) with respect to pure starbursts and pure AGNs (\( S \sim 3.6 \) and \( S \sim 0.04 \) respectively; Genzel et al. 1998). However, the determination of the continuum level is highly uncertain in the ISOPHOT spectra because of the presence of absorption features and the poor signal-to-noise ratio (S/N). In the optical and near-IR, the presence of an AGN is clearly revealed from the high \([O \text{ III}] / H\alpha\) ratio and from the presence of strong coronal lines (Vanzi et al. 2002).

The ISAAC spectrum presented here is probably the highest S/N L-band spectrum of a ULIRG so far. Thanks to the high signal and to the moderately high spectral resolution, the starburst and AGN indicators can be studied with unprecedented detail.

The signatures of the AGN activity in the L-band spectrum of IRAS 19254–7245 are quite clear: (1) the deep absorption at \( \sim 3.4 \) \( \mu \)m (rest frame) strongly suggesting the presence of a point source behind a screen of dusty gas; (2) the PAH feature at 3.3 \( \mu \)m with a much lower equivalent width than typical starburst-dominated sources; and (3) the rather steep continuum slope above \( \sim 3 \) \( \mu \)m, suggesting the presence of warm, AGN-heated dust. We discuss each of these points in the following.

3.1. The Absorption Feature at 3.4 \( \mu \)m

The broad absorption feature at \( \sim 3.4 \) \( \mu \)m (rest frame) is present in the spectra of many AGNs and ULIRGs (Imanishi & Dudley 2000; Imanishi 2000). We clearly detected such a feature in the spectrum of IRAS 19254–7245, with an optical depth \( \tau \sim 0.8 \). The absorption is believed to be due to the C–H stretching vibration in hydrocarbon dust grains (Sandford et al. 1991 and references therein). Imanishi & Maloney (2003) showed that an optical depth of this feature \( \tau_{3.4} \) higher than \( \sim 0.2 \) requires a centrally concentrated source, i.e., an AGN, unless dust absorption in the host galaxy is significant. Indeed, absorption features at 3.4 \( \mu \)m are commonly observed in AGNs (Imanishi 2000), but they are never found in galaxies known to be dominated by starbursts.

Since the same dust grains are present in the Galactic interstellar medium, the most detailed studies of the 3.4 \( \mu \)m absorption have been done on Galactic center sources (Sandford et al. 1991; Pendleton et al. 1994). In these cases, the high statistics available allow us to resolve the substructure of the absorption feature in at least two major components because of the \(-\text{CH}_1\) and \(-\text{CH}_2\) groups, respectively. In Figure 2b, we plot the ratio between the observed spectrum and the continuum.
The third absorption feature is due to the same hydrocarbon grains. The ratio between the two absorption peaks is an indication of the fraction of the infrared luminosity of IRAS 19254–7245. The similarity in the structure of the absorption feature indicates that the absorbing medium in IRAS 19254–7245 with observed wavelengths in the ranges 2.9–3.1, 3.3–3.5, and 3.8–4.1 \( \mu m \). A similar spectrum of the Galactic center source IRS 7 from Pendelton et al. (1994) is plotted in Figure 2a. The similarity between the two profiles is remarkable and suggests a common origin, i.e., vibrational transitions of –CH\(_3\) and –CH\(_2\) groups in hydrocarbon grains. [See the electronic edition of the Journal for a color version of this figure.]

A qualitative analysis is possible by comparing our data with the starburst template from the Sandford et al. (1991). The typical value for starburst galaxies is \( \sim 10^{-1} \) ergs cm\(^{-2}\) s\(^{-1}\), but in AGN-dominated sources, \( R \) is more than 1–2 orders of magnitude lower (Imanishi 2002). For IRAS 19254–7245, we have \( F_{\text{IR}} = 5.3 \times 10^{-10} \) ergs cm\(^{-2}\) s\(^{-1}\) and \( F_{3.4} = 2.1 \times 10^{-14} \) ergs cm\(^{-2}\) s\(^{-1}\). As a consequence, \( R = 3.9 \times 10^{-7} \). This indicator suggests that the detected starburst can account for only a small fraction of the infrared luminosity of IRAS 19254–7245.

Direct way to obtain a rough quantitative estimate of the AGN contribution to the infrared luminosity is to subtract a starburst template from the \( L \)-band spectrum and then compare the \( L \)-band flux (\( \lambda F_{\lambda} \), \( \lambda = 3 \mu m \)) with the total far-infrared flux \( F_{\text{IR}} \) as measured by IRAS. We expect that in case of AGN dominance, these two fluxes are approximately equal. We assumed that the PAH emission is entirely due to the starburst and that the starburst continuum is reproduced by a flat (\( f_{\lambda} \) = const) spectrum normalized in order to have \( EW_{3.4 \mu m} = 1000 \) Å in agreement with starburst spectra in Imanishi & Dudley (2000). The resulting “pure AGN” spectrum is steeper (\( \Gamma \sim 3 \), with \( T_{3.4 \mu m} = 0.9 \) and \( \lambda F_{\lambda} = 6 \times 10^{-12} \) ergs \( s^{-1} \) cm\(^{-2}\)).

The structure of a saturated hydrocarbon chain is \( \text{CH}_{3} \)-(CH\(_2\))\(_{n}\)-CH\(_{3}\); therefore, the ratio between the strength of the –CH\(_3\) and –CH\(_2\) absorption features is a direct measure of \( n \).

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we plot the 2002) and the ISOCAM point at 6 μm obtained at the New Technology Telescope (NTT; Vanzi et al. 1997). Interestingly, analyzing the 3–4 μm spectra of ULIRGs available in the literature, we note that a positive slope in the 3.5–4.0 μm continuum is only found in AGN-dominated sources. The opposite is not true: a few sources exist (Mrk 231, NGC 6240) with negative 3.5–4.0 μm slope and are known to host a powerful AGN from observations at other wavelengths. This issue will be discussed in further detail in a forthcoming paper (G. Risaliti et al., 2003, in preparation). At λ < 3.1 μm, an inversion of the slope is clearly seen. In Figure 3, we plot the L-band spectrum with the near-IR spectrum obtained at the New Technology Telescope (NTT; Vanzi et al. 2002) and the ISOCAM point at 6 μm (Laurent et al. 2000). The extrapolation of the continuum matches well both the K spectrum and the 6 μm point. This shows that the three observations are well cross-calibrated and that our flux calibration error is lower than ~5%.

The minimum in the L-band spectrum at ~3.1 μm is the absolute minimum in the optical-infrared spectrum of IRAS 19254–7245. At shorter wavelengths, the emission is dominated by radiation from the host galaxy since the AGN is highly obscured, and at longer wavelengths, the radiation is mainly due to the reprocessing of the AGN direct emission. Imanishi & Maloney (2003) detected a broad absorption feature at 3.1 μm in several ULIRGs that is due to ice-covered dust grains. In principle, we cannot exclude that the minimum observed at 3.1 μm is partly due to this effect. However, we note that if a significant fraction of carbonaceous dust grains are covered by ice, they do not contribute to the 3.4 μm absorption. This would imply that the optical extinction Aλ for a given rλ is even higher than that assumed in § 3.2. If this is the case, the correction to the observed 3 μm continuum would also be higher, worsening the problem of the too high 3 μm flux compared with the far-infrared emission.

3.3. Continuum Slope

The slope of the continuum at wavelengths λ > 3.7 μm is rather steep (fλ ∝ λ−2). This suggests a strong emission by warm dust, typical of AGN spectra (Granato, Danese, & Franceschini 1997). Interestingly, analyzing the 3–4 μm spectra of ULIRGs available in the literature, we note that a positive slope in the 3.5–4.0 μm continuum is only found in AGN-dominated sources. The opposite is not true: a few sources exist (Mrk 231, NGC 6240) with negative 3.5–4.0 μm slope and are known to host a powerful AGN from observations at other wavelengths. This issue will be discussed in further detail in a forthcoming paper (G. Risaliti et al., 2003, in preparation). At λ < 3.1 μm, an inversion of the slope is clearly seen. In Figure 3, we plot the L-band spectrum with the near-IR spectrum obtained at the New Technology Telescope (NTT; Vanzi et al. 2002) and the ISOCAM point at 6 μm (Laurent et al. 2000). The extrapolation of the continuum matches well both the K spectrum and the 6 μm point. This shows that the three observations are well cross-calibrated and that our flux calibration error is lower than ~5%.

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4. CONCLUSIONS

We presented a high S/N L-band spectrum of the ULIRG IRAS 19254–7245. The signatures of a powerful AGN dominating the energy output in the infrared are clear:

1. The broad absorption feature at ~3.4 μm suggests the presence of a powerful point source. The substructure of this feature shows that the absorption is due to hydrocarbon molecules consisting of chains of six to seven carbon atoms, rich in electronegative groups such as −CN and −OH.
2. The EW of the PAH emission feature at 3.3 μm, when the continuum is correctly estimated by taking into account the broad absorption at 3.4 μm, is typical of AGN-dominated sources.
3. The continuum at λ > 3.7 μm is rather steep, indicating the presence of hot dust.

The above conclusions show the potential of high S/N L-band spectroscopic observations with VLT-ISAAC. We are now completing a work in which we extend the present study to a sample of six more bright ULIRGs of the Genzel et al. (1998) sample (G. Risaliti et al. 2003, in preparation).

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