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LETTER

Letter to the Editor

Mid-infrared spectroscopy of the hyperluminous infrared galaxy IRAS P09104+4109⋆

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Abstract. We present mid-infrared spectroscopy of the hyperluminous infrared galaxy IRAS 09104+4109 based on observations with ISOCAM CVF. We have detected the emission peak around 8 μm as well as the absorption feature around 10 μm possibly due to silicate, providing evidence for a dusty torus around the central engine. Comparing the observational results with the dusty torus model studied by Pier & Krolik (1992), we show that the most mid infrared emission comes from a compact (a few pc in radius) dusty torus although the excess far infrared emission suggests the presence of an extended dusty torus with radius of $\sim$ 100 pc.

Key words: hyperluminous infrared galaxy (IRAS P09104+4109) – active galactic nuclei – infrared emission

1. Introduction

The current unified model of active galactic nuclei (AGNs) is based on a dusty torus around a central engine and so provides that the observational properties of AGNs are affected significantly by the viewing angle of the central engine (Antonucci & Miller 1985; Antonucci 1993). In addition, the dusty tori themselves are very important emitting agents because dust grains within the tori absorb the high-energy continuum radiation from the central engine and re-emit it in the infrared regime (Rees et al. 1969; Efstathious & Rowan-Robinson 1990; Pier & Krolik 1992, 1993; Granato & Denese 1994; Granato, Denese, & Franceschini 1996). It is, therefore, very important to study the properties of dusty tori directly. Since the dusty torus emission peaks at mid-infrared (e.g., 5 - 30 μm), mid-infrared spectroscopy of AGNs provides a direct test on the current paradigm. The Infrared Space Observatory (ISO; Kessler et al. 1996) launched by ESA in November 1995 has enabled us to perform such observations.

Using ISO, we have done mid-infrared spectroscopy of the hyperluminous infrared galaxy, IRAS P09104+4109 (hereafter P09104), which has been considered to be a dust-enshrouded type 2 quasar [Kleinmann et al. 1988 (hereafter K88); Hines & Wills 1993 (hereafter HW93); Fabian et al. 1994; Granato et al. 1996]. P09104 is the best target for the study of the dusty torus because 1) it has a pure AGN with huge infrared luminosity as well as a radio jet, 2) its host galaxy is a cD galaxy in a cluster of galaxies without any evidence for intense star formation, and 3) its redshift is intermediate (z = 0.4418), assuring the observational feasibility for ISO.

2. Observations

The observations have been made by ISO on 1996 April 8 (Revolution 143) and 10 (Revolution 145) with use of the ISOCAM (Cesarsky et al. 1996a) LW array which is a 32×32 infrared detector (Gallium doped silicon photoconductor array). In order to obtain a MIR spectrum of P09104, we used the circular variable filters (CVFs) which are a set of multi-layer thin film interference filters. The spectral resolution is $R = \lambda/\Delta\lambda = 35-51$. Our observing program consists of eight independent scans to cover the wavelength between 7.1 μm and 17.3 μm, corresponding to a range between 4.9 μm and 12 μm at the object rest frame. The integration time was 6000 seconds. The pixel field of view was 3 arcsec. Since the size of airy disk at 17 μm is 14 arcsec, we used the central 5×5 pixel data to extract the spectrum. We es-

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⋆ Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands, and the United Kingdom) and with the participation of ISAS and NASA.

timated the background by using the outer region of the central 9×9 pixels. After removing cosmic rays with the sigma clipping procedure in each CVF position, we performed the dark stripe removal, flat fielding, and sensitivity correction with use of the calibration files distributed by ESA. The extracted spectrum is shown in Fig. 1 together with the available photometric data of P09104 (K88; HW93; Moshir et al. 1992). Since the accuracy of absolute flux calibration for ISOCAM data is relatively uncertain at present, it is better to scale our data with use of the IRAS 12 μm flux given in the IRAS Faint Source Catalog (Moshir et al. 1992). Since our flux measured in the IRAS 12 μm band is weaker by a factor of 2.2 than the IRAS value, we have scaled our flux to the IRAS value by the same factor. The scaled spectrum is shown by the thick line after combining the eight scans. The combination spectrum was made by taking the spectral quality of the individual scans into account (i.e., the weight $\propto \sigma_{\rm rms}^{-2}$ where $\sigma_{\rm rms}$ is the rms noise).

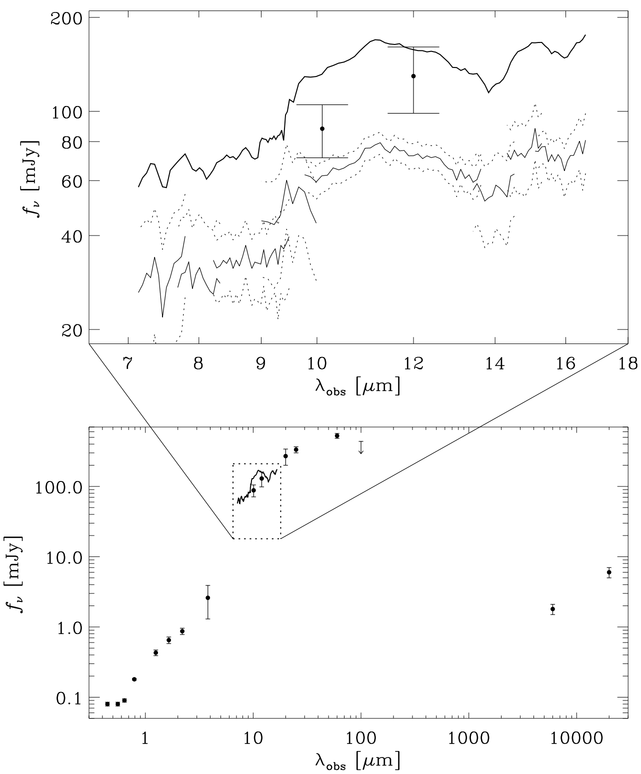

Fig. 1. The mid-infrared spectrum obtained with ISOCAM LW CVF system (*upper panel*). The eight independent spectra are shown in the lower part with one sigma rms noise. The upper spectrum shown by the thick line is the final spectrum scaled to the IRAS 12 μm flux. The right data point is the IRAS 12 μm flux while the left one is the ground-based photometry at 10 μm. The overall spectral energy distribution is shown in the lower panel together with our data. The abscissa is the observed wavelength in units of μm and the ordinate is the observed flux in units of mJy.

3. Results and Discussion

The MIR spectrum of P09104 obtained here shows the peak around 7.7 μm with the feature width (FWHM) of 1.76 μm. The possible absorption feature at 9.7 μm is also seen. These spectroscopic properties are quite similar to those of dusty tori around AGNs. Though a broad Pfund α line, one of hydrogen recombination lines, may appear at the rest wavelength 7.4 μm, its expected flux is much smaller by two orders than the observed one[1]. Also, a set of PAH (Polycyclic Aromatic Hydrocarbon) emission features at 6.4, 7.7, & 8.6 μm, might be present if the PAH particles are shielded by hard energy radiation from the central engine (cf. Voit 1992)[2]. However, these PAH features may not explain the observed smooth spectral feature around 7.7 μm. Therefore, we consider that the observed spectral properties are attributed to the dusty torus emission. Comparing our observations with some theoretical models of dusty torus emission, we discuss the nature of dusty torus in P09104.

Pier & Krolik (1992, hereafter PK92) investigated the thermally reradiated infrared spectra of the compact dusty tori surrounding the central engine of AGNs by using a 2-dimensional radiative transfer algorithm. The torus is a cylinder of dust with uniform density, characterized by the inner radius (a), outer radius (b), and height (h). A half opening angle of the torus is thus given as $\theta_{\rm open} = \tan^{-1}(2a/h)$. The important parameters describing models are: 1) the inner aspect ratio, (a/h), which is coupled with the covering factor, $f = 1 - \Omega/4\pi$, where Ω is the solid angle subtended at the source not covered by dust, 2) the effective temperature of the torus, $T_{\rm eff}$, which is roughly equal to the hottest dust temperature in the torus, 3) the radial and the vertical Thomson optical depth[3], $\tau_r = n_{\rm H}\sigma_{\rm T}(b-a)$ and $\tau_z = n_{\rm H}\sigma_{\rm T}h$, where $n_{\rm H}$ is the hydrogen number density and $\sigma_{\rm T}$ is the Thomson cross section, and 4) the viewing angle, i, between the symmetrical axis of the torus and the line of sight.

Now we compare the observed spectral energy distribution (SED) of P09104 with model results of PK92. Taking account of both the MIR SED and the NIR constraint posed by the L-band photometry (i.e., the L-band - 10 μm SED is very sensitive to the geometry of the inner edge in torus models), we have found that four models of PK92 are consistent in shape with the observed SED. These four models are compared with the observed SED in Fig. 2. Here we use the observed SED normalized by

[1] We derived an empirical relationship, $\log L({\rm H}\alpha)/L_{\rm bol} \simeq -2.01 \pm 0.2$ for Class A (i.e., *bare, minimally reddened*) active galactic nuclei studied by Ward et al. (1987). Given $L({\rm Pf}\alpha) = 0.0064 L({\rm H}\alpha)$ for Case B recombination (Wynn-Williams 1984), we estimate an expected flux of Pfα emission, $f({\rm Pf}\alpha) \simeq 7 \times 10^{-15}$ erg s^{-1} cm^{-2}.

[2] We cannot, however, rule out another possibility that these emission features are attributed to carbonaceous grains heated transiently in regions of high radiation field (cf. Cesarsky et al. 1996b)

[3] The Thomson optical depth, τ = 1 corresponds to the hydrogen column density, $N_{\rm HI} = 1.5 \times 10^{24}$ cm^{-2}, or to the visual extinction, A_V = 787 mag (PK92).

the bolometric luminosity ($L_{\rm bol}$ = 7 × $10^{12} L_\odot$)[4] in order to make consistent comparisons with the models of PK92. These comparisons suggest that the data are almost consistent with the model with (1) a/h = 0.1, (2) $T_{\rm eff}$ = 1,000 K, (3) τ_r = 1 and τ_z = 1, and (4) the viewing angle i = 60°. The inner aspect ratio gives a covering factor, $f \simeq 0.98$. Since the hard X-ray emission is blocked significantly (Fabian & Crawford 1995; Crawford & Vanderriest 1996), the large optical depths seems reasonable. Although we cannot conclude that this is a unique model, given both the bolometric luminosity and the effective temperature of the torus, one may estimate the torus properties following PK92 and Pier & Krolik (1993). The results are summarized in Table 1.

Table 1. The most plausible dusty torus model for P09104

a/h[1]	i[2] (degree)	f[3]	a[4] (pc)	b[5] (pc)	h[6] (pc)	$M_{\rm gas}$[7] ($M_\odot$)
0.1	60	0.98	1.9	2.3	19	4×10^7

[1] The inner aspect ratio. [2] The viewing angle. [3] The covering factor. [4] The inner radius of the torus. [5] The outer radius of the torus. [6] The full height of the torus. [7] The gas mass associated with the torus [see equation (1) in PK92].

Though this best model may explain the MIR property of P09104, it cannot explain the excess emission at FIR (see Fig. 2). Since there is no evidence for circumnuclear starburst in P09104 (K88; HW93), this excess emission may be attributed to the black body radiation of 70 K, provided that the dust emissivity is proportional to λ^{-1}. Its luminosity amounts to $\sim 1.1 \times 10^{12} L_\odot$, giving a dust mass of $M_{\rm dust}$(FIR) $\sim 6 \times 10^6 M_\odot$ based on the formula given in Eales & Edmunds (1996) using a mass absorption coefficient of 25 cm^2 g^{-1} at 100 μm (Hildebrand 1983). The gas mass associated with this dust component is estimated to be $M_{\rm gas}$(FIR) $\sim 10^9 M_\odot$ at most. We may consider that this component comes from dust grains extended around the nuclear dusty torus (see Pier & Krolik 1993). With an assumption that the dust is optically thin near the peak of the SED at 40 μm and using the optical constants for dust grains given in Draine & Lee (1984), K88 derived the equilibrium size of 130 pc with the gas mass of $2\times10^7 M_\odot$ for the dust emitting region in P09104 assuming the dust temperature of 120 K. Here we also mention about the model analysis by Granato et al. (1996). While PK92 assumed the cylindrical geometry with uniform density in the torus, Granato et al. (1996) adopted the exponential decrease of the gas/dust density in the vertical direction and proposed the following geometrical parameters for the dusty torus of P09104; $a(= r_{\rm min})$ = 0.6 pc, $b(= r_{\rm max})$ = 316 pc, $M_{\rm dust}$ = 2.6 × $10^6 M_\odot$, and the viewing angle $i \simeq 45°$. Though this torus is larger and more massive than that given in Table 1, their model can explain the FIR excess as well as the MIR SED. Since the dusty torus may have spatial inhomogeneity, a part of nuclear continuum radiation could escape from the inner high-density region, giving rise to the formation of a warm, extended dusty torus around the *nuclear* torus. We, therefore, consider that the observed FIR excess emission of P09104 is attributed to the emission from this extended dusty torus whose size is about 100 pc in radius, inferred from K88 and Granato et al. (1996). A schematic illustration for the dusty torus of P09104 is shown in Fig. 3.

[4] We adopt a Hubble constant H_0 = 100 km s^{-1} Mpc^{-1} and a deceleration parameter q_0 = 0.5.

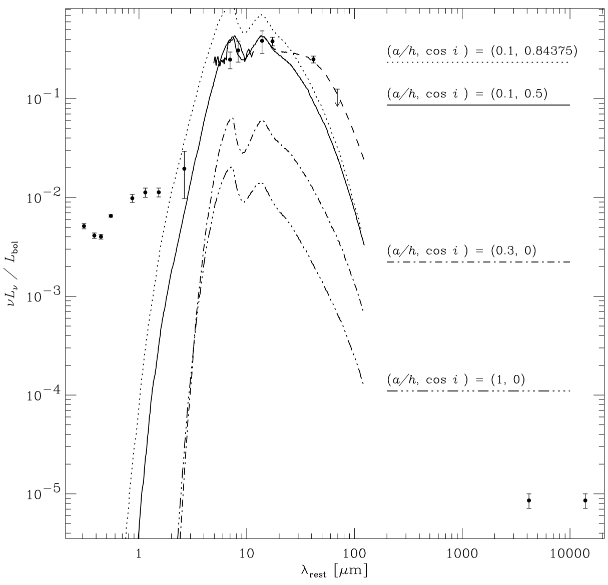

Fig. 2. The comparison of the observed SED with the theoretical models of dusty torus made by PK92. The abscissa is the rest-frame wavelength. The ordinate is adjusted to the expression of PK92. All the models have $\tau_{\rm r} = \tau_{\rm h}$ = 1 and $T_{\rm eff}$ = 1,000 K. The best model (the thick line) is that for (a, h) = 0.1 and cos i = 0.5. The excess FIR emission may be attributed to the extended torus emission with the black body radiation (T = 70 K) which is shown by the dashed line.

The present observation has confirmed that P09104 is the dust-enshrouded type 2 quasar. We would like to stress that the nuclear dusty torus is compact (i.e., less than 10 pc), and the associated gas mass is only $\sim 1 \times 10^7 M_\odot$ although there presents the extended ($\sim$ 100 pc), more massive ($\sim 1 \times 10^9 M_\odot$) torus. It is likely that this gas may be supplied from the massive cooling flow whose mass flow rate is $\sim 1000 M_\odot$ y^{-1} (Fabian & Crawford 1995; Crawford & Vanderriest 1996). The accreting gas mass would exceed $\sim 10^9 M_\odot$ only within $\sim 10^6$ years.

Finally, we consider what P09104 is again. As discussed by K88 and HW93, the nature of the radio jet is unusual although the jet shows a double-lobed structure like that of Fanaroff-Riley II sources (FR II); 1) the prominence of counterjet (i.e., the low sideness ratio), 2) the marginal radio power between FR I and FR II sources, 3) the unusually large ratio of core to lobe flux density, and 4) the unusually steep spectra of the core and the hot spots. These anomalous properties may be partly due to the jet environment (i. e., the jet propagation in the massive cooling

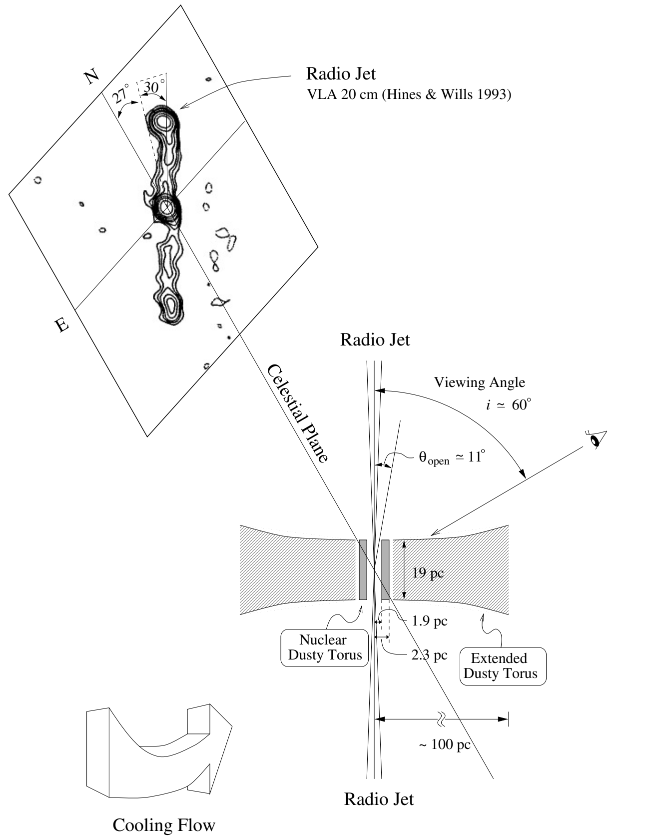

Fig. 3. The dusty torus model for P09104. The compact dusty torus given in Table 1 is shown by the dark shaded regions while the extended one is shown by the light ones. The radio jet at λ=20 cm shown in the upper left corner is taken from HW93.

flow). Our observations suggest the angle between the actual jet and the celestial plane $\simeq 30^\circ$ (see Fig. 3). Since it is considered that the radio jet emanates along the torus axis, we obtain the actual half length of the jet, $l_{\rm jet} \simeq 43.5$ kpc, being much shorter than typical lengths of powerful radio jets. If we assume the jet velocity of $v_{\rm jet} = \alpha c$ where c is the light velocity in the vacuum and α is a constant smaller than 1, the characteristic timescale of the jet is estimated to be only $\tau_{\rm jet} = 1.4 \times 10^5 \alpha^{-1}$ years. For most radio jets in AGNs, $\alpha \sim 1$. However, the prominence of the counterjet implies that the jet speed is non-relativistic. Even if $\alpha \simeq 0.1$, we obtain $\tau_{\rm jet} \sim 10^6$ years. Since this timescale can be regarded as the elapsed time after the onset of the nuclear activity in P09104, we may consider that the AGN in P09104 is in a relatively young phase.

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References

Antonucci, R., & Miller, J. S. 1985, ApJ, 297, 621
Antonucci, R. 1993, ARA&A, 31, 473
Cesarsky, C., et al. 1996a, A&A, 315, L32
Cesarsky, D., Lequex, J., Abergel, A., Perault, M., Palazzi, E., Madden, S., & Tran, D., 1996b, A&A, 315, L309
Crawford, C. S., & Vanderriest, C. 1996, MNRAS, 283, 1003
Draine, B. T., & Lee, H. M. 1984, ApJ, 285, 89
Eales, S. A., & Edmunds, M. G. 1996, MNRAS, 280, 1167
Efstathious, A., & Rowan-Robinson, M. 1990, MNRAS, 245, 275
Fabian, A. C., & Crawford, C. S. 1995, MNRAS, 274, L63
Fabian, A. C., et al. 1994, ApJ, 436, L51
Granato, G. L., & Danese, L. 1994, MNRAS, 268, 235
Granato, G. L., Danese, L., & Franceschini, A. 1996, ApJ, 460, L11
Hildebrand, R. H. 1983, QJRAS, 24, 267
Hines, D. C., & Wills, B. J. 1993, ApJ, 415, 82 (HW93)
Kessler, M. et al. 1996, A&A, 315, L27
Kleinmann, S. G., Hamilton, D., Keel, W. C., Wynn-Williams, C. G., Eales, S. A., Becklin, E. E., & Kuntz, K. D. 1988, ApJ, 328, 161 (K88)
Moshir, M. et al. 1992, *Explanatory Supplement to the IRAS Faint Source Survey*, Version 2, JPL-D-10015 8/92 (Pasadena: JPL)
Pier, E. A., & Krolik, J. H. 1992, ApJ, 401, 99 (PK92)
Pier, E. A., & Krolik, J. H. 1993, ApJ, 418, 673
Rees, M. J., Silk, J. I., Werner, M. W., & Wickramasinghe, M. C. 1969, Nature, 223, 788
Voit, G. M. 1992, MNRAS, 258, 841
Ward, M. J., Elvis, M., Fabbiano, G., Carleton, N. P., Willner, S. P., & Lawrence, A. 1987, ApJ, 315, 74
Wynn-Williams, C. G. 1984, in "Galactic and Extragalactic Infrared Spectroscopy", eds. M. F. Kessler & J. P. Phillips, D. Reidel Publishing Company

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