An Infrared View of Local Universe AGN

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Abstract. We summarize recent results on the infrared (IR) nuclear properties of Seyfert galaxies. 100% of all Seyfert 1 − 1.9s and ≃ 50% of all Seyfert 2s in the CfA and RSA samples observed with HST/NICMOS show nuclear point sources at 1.6 μm. We find that the unresolved emission is variable in 9 out of the 14 Seyferts with duplicate observations, indicating a non-stellar origin. We have also put together non-stellar 0.4 − 16 μm spectral energy distributions (SEDs) for the entire CfA sample of Seyfert galaxies. The shape of the SEDs for a complete sample of AGN can be used to constrain torus models. We report a good correlation between the IR and hard X-ray luminosities of local universe AGN suggesting that their mid-IR emission is approximately an isotropic property, and thus can be used as an indicator of the AGN luminosity. Finally we show that the hard X-ray and mid-IR luminosities appear to be related to the black hole mass in AGN.

1. Introduction

The advent of new infrared (IR) facilities (both space and ground-based) with superb spatial resolution and sensitivity is allowing us to make significant progress toward the understanding of the IR nuclear properties of local universe AGN. The IR emission in AGNs (Seyfert galaxies and radio quiet quasars) is often interpreted as produced by hot dust in a torus/disk configuration (e.g., Barvainis 1987; Sanders et al. 1989; Pier & Krolik 1993). However, until recently, the nuclear non-stellar IR continuum of Seyfert 2 galaxies has eluded us because of the dominance of the stellar emission shortward of 3 μm (e.g., Alonso-Herrero et al. 1996). In this paper we summarize recent results obtained by our group on the IR nuclear properties of Seyfert galaxies in the local universe.

2. Unresolved Continuum Sources at 1.6 μm

We have analyzed HST/NICMOS 1.6 μm observations of 112 Seyfert galaxies and found that ≃ 50% of the Seyfert 2s in the Revised Shapely-Ames (RSA) Catalog and CfA redshift sample contain unresolved nuclear continuum sources at 1.6 μm. Most Seyfert 1 − 1.9s display unresolved nuclear continuum sources at this wavelength. These unresolved sources have 1.6 μm fluxes of order 1 mJy, near-IR luminosities of order 10^{41} erg s^{-1}, and absolute magnitudes M_{H} ≃ −16. Non-Seyfert galaxies from the RSA Catalog display significantly fewer (≃ 20%)
nuclear unresolved sources with lower luminosities, which could be due to compact star clusters. We have also found that the luminosities of the unresolved Seyfert 1.0–1.9 sources at 1.6 μm are correlated with the [O iii] λ5007 and hard (2 – 10 keV) X-ray luminosities, implying that these sources are non-stellar.

We find no strong correlation between the unresolved 1.6 μm fluxes and hard X-ray or [O iii] λ5007 fluxes for the pure Seyfert 2s. These galaxies also tend to have lower 1.6 μm luminosities compared to the Seyfert 1.0 – 1.9 galaxies of similar [O iii] luminosity. This is in agreement with the findings of Alonso-Herrero et al. (1997) using L (3.5 μm) nuclear fluxes. Either large extinctions (A_V ≃ 20 – 40 mag) are present toward their continuum-emitting regions or some fraction of the unresolved sources at 1.6 μm in Seyfert 2s are compact star clusters (see Quillen et al. 2001 for more details).

Further evidence for the non-stellar origin of the unresolved nuclear emission at 1.6 μm comes from variability shown by 9 of the 14 nuclei studied in Quillen et al. (2000). The variability is at the level of 10% – 40% on timescales of ≃ 1 – 14 months, depending upon the galaxy. A control sample of Seyfert galaxies lacking unresolved sources and galaxies lacking Seyfert nuclei show less than 3% instrumental variation in equivalent aperture measurements.

Figure 1. Distributions of the IR (1 – 16 μm) spectral indices (f_ν ∝ ν^{-α_{IR}}) for 51 Seyferts in the CfA sample. The sample has been broken up in different Seyfert types as derived from optical spectroscopy.

3. SEDs of the CfA Seyfert galaxies

We have put together nuclear SEDs in the 0.4 – 16 μm spectral range for the entire CfA sample of Seyfert galaxies, including those LINERs reclassified as Seyferts by later spectroscopic studies (see Alonso-Herrero et al. 2002b). We find that the spectral indices (f_ν ∝ ν^{-α_{IR}}) of the unresolved AGN emission in the region 1 – 16 μm vary from α_{IR} ∼ 0.9 to 3.8. The shapes of the spectra are correlated with the Seyfert type in the sense that steeper nuclear SEDs (νf_ν increasing with increasing wavelength) tend to be found in Seyfert 2s and flatter SEDs (νf_ν ∼ constant) are in the Seyfert 1 – 1.5s (see Fig. 1). The majority of galaxies optically classified as Seyferts 1.8s and 1.9s display values of α_{IR} either as in type 1 objects (mean for type 1s α_{IR} = 1.5 ± 0.4), or intermediate between
Seyfert 1s and Seyfert 2s (Fig. 1). The SED of intermediate Seyfert 1.8–1.9s may be consistent with a pure Seyfert 1 SED viewed through moderate amounts ($A_V < 5$ mag) of foreground galaxy extinction.

Torus models usually adopt high equatorial opacities to reproduce the IR properties of Seyfert 1s and 2s (e.g., Pier & Krolik 1993; Efstathiou & Rowan-Robinson 1995), resulting in a dichotomy of SEDs — flat for type 1s, and steep for type 2s. Such dichotomy is not observed in the CfA Seyferts, and in particular there is a wide range of observed $\alpha_{IR}$ in type 2s (Fig. 1). The lack of steep SEDs, and large numbers of objects with intermediate spectral indices cannot be reconciled with predictions from existing optically thick torus models. Possible modifications to existing torus models include low optical depth tori, clumpy dusty tori and high optical tori with an extended optically thin component.

![Figure 2](image)

Figure 2. Left panel: Relation between the 10 $\mu$m nuclear luminosity and the BH mass. Filled stars are PG quasars, crosses are Seyfert 1s, open triangles are narrow-line Seyfert 1s, and filled squares are Seyfert 2s. Right panel: Same as left panel, but for the hard X-ray (2–10 keV) luminosity and BH mass.

4. Mid-IR emission of AGN, an indicator of the AGN luminosity and black hole mass?

The hard X-ray (2–10 keV) emission of Seyfert galaxies is known to be a good indicator of the intrinsic luminosity of the AGN for those cases where it is transmitted through the torus, that is, in Compton thin galaxies. Other proposed isotropic (that is, not dependent on the viewing angle to the AGN) indicators of the AGN emission in Seyfert 1s and Seyfert 2s include the [O III] $\lambda$5007 luminosity (Mulchaey et al. 1994; Heckman 1995) or the nonthermal 1.45 GHz radio continuum (Heckman 1995).

We find a good correlation between ground-based 4.8 $\mu$m and ISO 9.7 $\mu$m and hard X-ray fluxes and luminosities for both Seyfert 1s and Compton thin
(\(N_H \leq 10^{24} \text{ cm}^{-2}\)) Seyfert 2s (see Alonso-Herrero et al. 2001, also Krabbe et al. 2001). This indicates that the mid-IR emission in Seyfert galaxies can be used as a measure of the AGN luminosity. The improved correlations at 4.8 and 9.7 \(\mu\)m with respect to those at shorter wavelengths (Alonso-Herrero et al. 1997, and Section 2) are explained in terms of the reduced extinction. Some Compton thick sources (e.g., NGC 1068 and Mrk 533) are bright IR sources suggesting that the component responsible for the bulk of the IR emission in Seyfert galaxies is more visible from all viewing angles than that responsible for the hard X-ray emission.

We have also compiled a heterogeneous sample of local AGN that includes Seyfert 1 galaxies, Seyfert 2 galaxies, and PG quasars to investigate for the first time the relation between black hole (BH) mass and mid-IR nuclear emission (Fig. 2, left panel). We find a clear relation between the BH mass and the 10 \(\mu\)m nuclear luminosity for these local AGNs. There are no significant differences between type 1 and type 2 objects, implying that the reprocessing of the 10 \(\mu\)m nuclear emission is not severely affected by geometric and optical depth effects. We also confirm that the BH mass is related to the 2–10 keV X-ray luminosity, but only for Compton-thin galaxies (Fig. 2, right panel). Our results show that rest-frame 10 \(\mu\)m and hard X-ray luminosities (especially the former, which is applicable to all AGN types) may be used to derive BH masses at high redshift and to probe their cosmological evolution (see Alonso-Herrero et al. 2002a).

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