MODELLING THE INFRARED CONTINUUM OF CENTAURUS A

D.M. Alexander[1], A. Efstathiou[2], J.H. Hough[3], D. Aitken[3], D. Lutz[4], P. Roche[5], & E. Sturm[4]

[1]SISSA, via Beirut 2-4, 34013 Trieste, Italy
[2]Astrophysics Group, Imperial College, London, UK
[3]Department of Physical Sciences, University of Hertfordshire, Hatfield, Hertfordshire, UK
[4]Max-Planck-Institut fur extraterrestrische Physik, Garching, Germany
[5]Department of Astrophysics, Oxford University, Oxford, UK

ABSTRACT

We present ISOPHOT-S, ISOSWS and 8 to 13 μm ground based observations of Centaurus A that show prominent PAH and silicate features. These and other data are used to construct a model for the infrared continuum. We find that in a nuclear sized aperture ($\sim$4 arcsec, $\sim$60 pc) the SED is characteristic of emission from a starburst and AGN torus; in larger apertures an additional component of cirrus emission is required. Based on our model, the torus diameter is estimated to be 3.6 pc and the best fitting inclination angle of the torus is 45 degrees. This result has implications for the detectability of tori in low power AGN and in particular for the use of the IRAS 60/25 μm flux ratio as an indicator of the torus inclination.

Key words: active-galaxies; individual; Cen A; nuclei-galaxies; galaxies-radiative transfer.

1. INTRODUCTION

Rowan-Robinson and Crawford (1989) attribute the infrared (IR) spectra of galaxies to a mixture of up to 3 components: i) general disc emission from grains heated by the interstellar radiation field (cirrus), ii) a Seyfert component peaking in the mid-infrared and iii) a starburst component peaking at about 60 μm. Essentially all of these sources arise from the thermal reprocessing of ultra-violet and other high frequency photons by the dust within these objects. The dust grains re-radiate the absorbed energy in the IR, with the resultant spectrum dependent on the distribution of dust grain temperatures. For the starburst and Seyfert components, the clouds of dust are optically thick, even to IR photons, so radiative transfer effects are important.

Centaurus A, the famous southern radio (FRI) counterpart to NGC5128, identified by Bolton, Stanley and Slee (1949), at a distance of approximately 3.1 Mpc (Tonry and Schechter 1990) is the closest active galaxy to us. It is a multi-faceted object, showing evidence of a merger (Mirabel et al. 1998), starburst and AGN activity, with HII regions, shells, jets, optical filaments and a warped dust lane.

Evidence of star formation is most apparent in the dust lane that intersects the host galaxy NGC5128. Marston & Dickens (1988) found that their 12 μm IRAS DSD observations followed the Hα emission, along the dust lane, and hence the regions of star formation. They modelled their 12, 25, 60 and 100 μm observations as a cirrus spectrum of small and large grains heated by the interstellar radiation with two grain temperatures - hot (240 K) small grains and cooler (30 K) large grains. Evidence of starburst activity comes from enhanced far-IR and sub-mm nuclear emission that shows a structure offset from the dust lane (e.g. Hawarden et al. 1993) and from the high star formation rate, which is typical of a starburst galaxy (Eckart et al. 1990). Evidence of AGN activity comes from the radio jets/lobes (e.g. Clarke, Burns & Norman 1992) and variable x-ray emission (e.g. Morini, Anselmo & Molteni 1989) whilst evidence of a Seyfert-like dusty torus comes from the high optical depth to the nucleus (e.g. Blanco, Ward & Wright 1990).

2. OBSERVATIONS AND DATA

The observations used to constrain the models are an array of published and unpublished data, taken from a variety of sources and grouped into 3 aperture sizes: a small nuclear aperture of $\sim$4 arcsec, an intermediate aperture of $\sim$20 arcsec and a large aperture of $\sim$90 arcsec.

The ISOPHOT-S observations (intermediate aperture) have not been presented before, see Figure 1. The observations have been reduced with PIA without additional modifications. The zodiacal light contributions have been removed using a chopped measurement. The ISOPHOT-S spectrum consists of two parts - PHT_SL (6 to 12 μm) and PHT-SS (2.5 to 5.5 μm). Clearly seen in the spectrum are the deep 9.7 μm silicate absorption feature and PAH emission features, however importantly, PAH emission at 3.3 μm is not clearly detected.

Proceedings of the Conference "The Universe as seen by ISO", Paris, France, 20–23 October 1998 (ESA SP-427, March 1999)

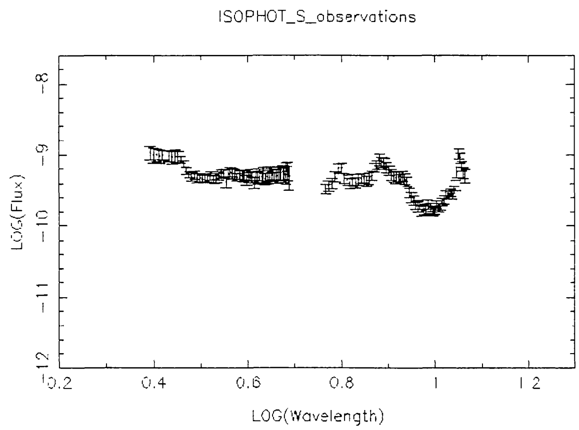

Figure 1. ISOPHOT-S observations. The flux units are ergs^{-1}cm^{-2}. The wavelength units are LOG(microns).

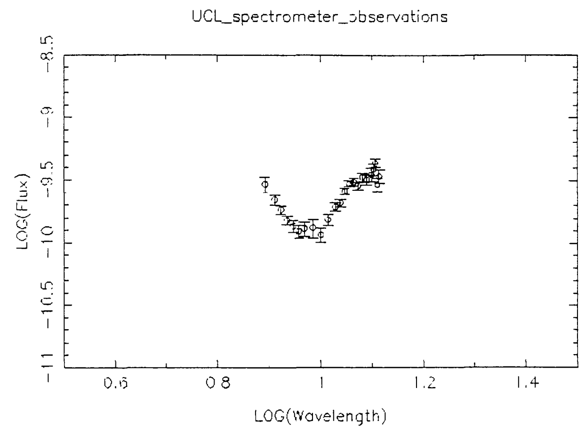

Figure 2. UCL spectrometer observations. The units are the same as in figure 1.

The ISOSWS observations (intermediate aperture) presented here are the continuum points. The emission line spectrum, details of the observations and data reduction will be presented in Sturm et al (in preparation). The continuum points were determined by a second order polynomial fit to the line free regions of the data. The error bars represent the uncertainty in flux calibration - the RMS noise level is insignificant by comparison. No correction has been made for the different aperture sizes at the different wavelengths.

Due to the problem of starlight contamination, and some uncertainty in the flux levels at the short wavelength end of these ISO spectra, the data shortward of 6 μm are not used in the model fitting.

The UCL spectrometer observations (nuclear aperture) have not been presented before, see Figure 2. The silicate feature at 9.7 μm is clearly detected. In addition there appears to be a component of 11.3 μm PAH and 12.8 μm [NeII] emission.

Additional data was obtained from the literature. The near-IR points (nuclear aperture) were taken from Packham et al (1996) and have had the stellar contribution removed. The sub-mm points (intermediate and large aperture) were taken from Hawarden et al (1993) and have been corrected for non-thermal contributions. The 12, 25, 60 and 100 μm large aperture points were taken from Marston and Dickens (1988) and are IRAS DSD observations.

3. THE MODEL COMPONENTS

The proposed model for Centaurus A is a combination of a number of components. The first component is the AGN dusty torus, based on the NGC1068 tapered disc infrared model of Efstathiou, Hough and Young (1995) which assumed a quasar-like central continuum source illuminating an optically and geometrically thick dusty torus. The main model parameters are: opening half-angle of the toroidal cone (θ), ratio of the inner and outer radii (r1/r2), ratio of the height to outer radius (h/r2), equatorial optical depth ($e_{\tau uv}$), dust sublimation temperature (T1) and radial dependence of the density distribution ($r^{-\beta}$). The second and third components are the starburst and cirrus models of Efstathiou, Rowan-Robinson & Siebenmorgen (1998). The cirrus spectrum is assumed to arise from 12,000 K stars centrally illuminating a diffuse optically and geometrically thin dust shell. The starburst is modelled as an ensemble of giant molecular clouds centrally illuminated by hot stars. The stellar population is modelled in terms of the population synthesis models of Bruzual and Charlot (1993) and the giant molecular clouds evolve with time due to the expansion of the HII regions. Additional information on the model components is given in Alexander et al. (1998).

To take into account of dust lane absorption, radiation from the torus and starburst are visually extincted by 10 mags, essentially the same as the value adopted by Packham et al (1996). The cirrus is not extincted since it is itself associated with the dust lane. The extinction model used assumes the grain model and interstellar extinction curve of Rowan-Robinson (1992).

4. THE CENTAURUS A MODEL

For small apertures, and at IR wavelengths below 12 μm, it was assumed that the SED would be dominated by radiation from the torus, seen through the dust lane. Therefore the torus model is fitted to this wavelength range, which includes the 9.7 μm silicate feature. In fitting to larger apertures, a contribution from the smaller apertures is included and any additional components required.

The torus parameters were set to be the same as those in the Efstathiou, Hough & Young (1995) model for NGC1068 (θ=30 degrees, r1/r2=0.01, h/r2=0.1, $e_{\tau uv}$=1,200, T1=950 and β=-1) and the SED was calculated for different values of inclination (the angle between the polar axis and the line of sight). No value of inclination gave a simultaneously good fit to both the near-IR continuum and the silicate feature, with the former best fit by 40 degrees and the latter by 70 degrees. The observed silicate feature shows a feature at 11.3 μm which is probably PAH emission, therefore a component of starburst was added. This provided an excellent fit to the silicate feature, with roughly equal components of torus and starburst for wavelengths less than 60 μm, with the torus at an inclination of 45 degrees, see Figure 3.

For larger apertures a component of cirrus emission was required. For completeness, the contribution this would make in the nuclear aperture is shown in Figure 3 (the cirrus component was determined assuming constant surface brightness, as implied from the fits to the larger apertures).

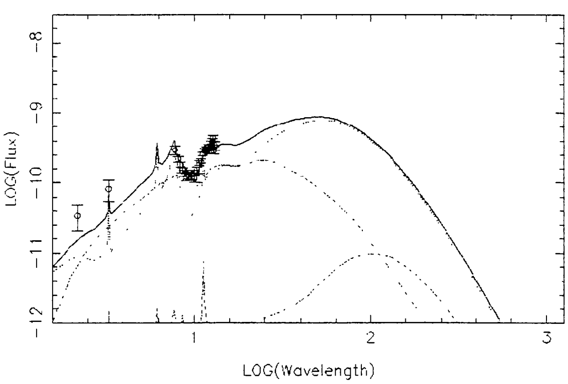

Figure 3. The model fit to the nuclear aperture data points. At the 100 μm wavelength: the lowest intensity model component is the cirrus, the highest intensity component is the starburst and the component in between is the torus. The units are the same as in Figure 1.

In the intermediate aperture, the torus component is kept fixed and an additional contribution from the starburst is added, producing a reasonable fit to the intermediate aperture data points for the silicate feature and IR continuum below 25 μm. The PAH features and the continuum at longer wavelengths showed that an additional component was required. Observations (e.g. Marston & Dickens 1988) suggest that this additional component is cirrus emission from stars within the dust lane. By slightly reducing the contribution from the starburst and adding a component of cirrus, an excellent fit to all the data points is obtained, see Figure 4.

The observed size of the starburst component (e.g., Hawarden et al. 1993) limits the contribution it should have in the large aperture. Whilst there should be an additional contribution from the starburst, the cirrus emission, which is associated with the dust lane, and so is widespread, should contribute

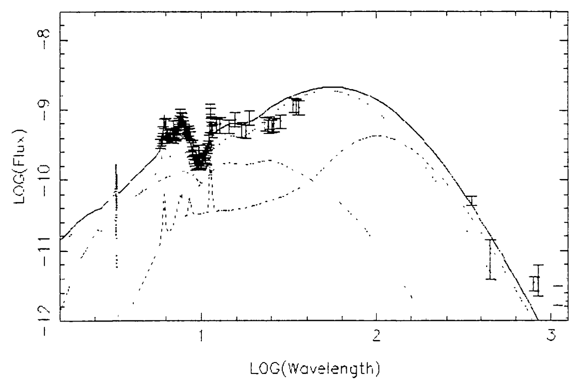

Figure 4. The model fit to the intermediate aperture data points. The model components and units are the same as in Figure 3.

significantly more. The best fit is obtained with a relatively small increase in the starburst contribution and a significant increase in the cirrus contribution, see Figure 5.

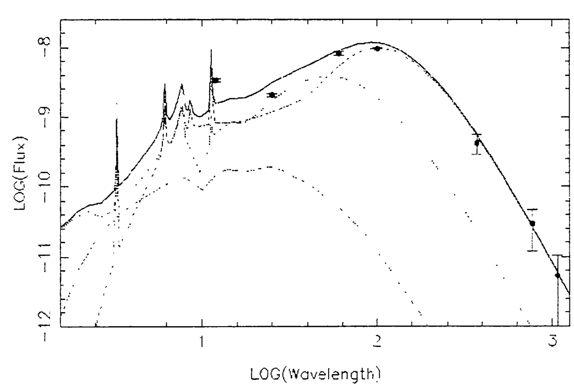

Figure 5. The model fit to the large aperture data points. The model components and units are the same as in Figure 3.

5. DISCUSSION

The complete model includes contributions from torus, starburst and cirrus in all apertures. The model fit in the nuclear aperture is quantitatively similar to that found by Laurent et al. (these proceedings), with ISOCAM CVF observations and AGN and starburst observational templates.

The opening half-angle of the torus cone is very similar to that of the 'cones' in the recently published HST nuclear Paα image (Schreier et al. 1998), and if it is assumed that these observations are of ionisation cones, rather that the suggested warped accretion disc, the cone opening half-angle is constrained between 30 and 40 degrees. Extinction to the 2.2 μm region can be estimated by comparing the flux for the face-on torus to the 45 degree inclined torus and is 2.6 mags, equating to a visual extinction of 23 mags. This degree of extinction is consistent with the analysis of Meadows & Allen (1992) and suggests that the near-IR emission region is considerably less extincted than the x-ray region (70 mags, Blanco, Ward & Wright 1990).

Based on this model, the torus diameter is calculated to be 3.6 pc, assuming a distance of 3.1 Mpc, placing it easily within the nuclear aperture. This is significantly smaller than that actually observed in other galaxies (e.g., $\sim$1 kpc for MG0414+0534 (Oya et al. these proceedings), $\sim$200 pc for NGC1068 (Young et al. 1996), $\sim$100 pc for NGC4261 (Jaffe et al. 1993) and $\sim$50 pc for NGC4151 (Mundel et al. 1995). However, although of a small diameter, this model does not support the even smaller diameter tori of the Pier & Krolik (1992) model.

Possible observational support for the small torus size estimate comes from the 2.3 GHz radio observations of the nuclear sub-arcsecond scale jet and counter jet (Jones et al, 1996). These images show the core to be completely absorbed between the jet and counter jet, attributed to a gaseous disc or torus of 0.4 to 0.8 pc. The model torus, with an inclination of 45 degrees would present a 1.4 pc absorption band; very similar to the size of the radio core absorption.

Within the context of unified theories the inclination of the torus is a crucial parameter in determining whether an AGN is a Type 1 or Type 2. Various studies have suggested that the IRAS 60/25 μm flux ratio is an indicator of torus inclination with high or low ratios implying edge-on to face-on torus inclinations. The combination of all the model components gives a 60/25 μm flux ratio of 9.4, although the actual torus 60/25 micron flux ratio is only 0.7. The torus inclination implied from this study is identical to that found for NGC1068 (Efstathiou, Hough & Young 1995) and yet the IRAS 60/25 μm flux ratio for NGC1068 is only 2.1. If the torus was as powerful as that in NGC1068, or a smaller 'nuclear' sized aperture was used, the 60/25 μm flux ratio would be more indicative of the torus inclination but within the large IRAS sized aperture, the torus is dominated by other more powerful IR emitting components.

A comparison of the mean IRAS 60/25 μm flux density ratios of the extended 12 μm sample of galaxies, which is considered statistically complete on 12 μm flux, gives a mean of 4.1$\pm$2.9 for the Seyfert 1s and 4.5$\pm$3.0 for the Seyfert 2s (Andy Thean, private communication). This suggests that this colour ratio cannot distinguish between Type 1 and Type 2 AGN and so cannot be a reliable indicator of the torus inclination.

The IRAS 60/25 μm flux density ratio is more likely to provide a ratio of the AGN to star formation components. Evidence for this comes from the 60 μm to 6 cm flux correlation (Wilson 1988) which works only if the radio jet/lobe AGN emission is removed (Peter Bartel, private communication), thereby strongly suggesting that the 60 μm flux is coming from star formation and starburst regions. Additional evidence comes from the ISOLWS observations of NGC1068 (Spinoglio et al. these proceedings) where the far-IR continuum is almost indistinguishable to that of the archetypal starburst galaxy M82.

REFERENCES

Alexander, D.M., Efstathiou, A., Hough, J.H. et al. 1998, MNRAS, in press

Blanco, P.R., Ward, M.J., Wright, G.S. 1990, MNRAS, 242, 4P

Bolton, J.G., Stanley, G.J., Slee, O.B. 1949, Nature, 164, 101

Bruzual, G., Charlot, S. 1993, ApJ, 405, 538

Clarke, D.A., Burns, J.O., Norman, M.L. 1992, ApJ, 395, 444

Eckart, A., Cameron, H., Rothermal, H. et al. 1990, ApJ, 363, 451

Efstathiou, A., Hough, J.H., Young, S. 1995, MNRAS, 277, 1134

Efstathiou, A., Rowan-Robinson, M., Siebenmorgan, R. 1998, MNRAS, in press

Hawarden, T.G., Sandell, G., Matthews, H.E. et al. 1993, MNRAS, 260, 844

Jaffe, W., Ford, H.C., Ferrarese, L. et al. 1993, Nature, 364, 213

Jones, D.L. et al. 1996, ApJ, 466, L63

Marston, A.P., Dickens, R.J., 1988, A&A, 193, 27

Meadows, V., Allen, D., 1992, Proc.ASA, 10(2), 104

Mirabel et al. 1998, A&A, 333, L1

Morini, M., Anselmo, F., Molteni, D., 1989, ApJ, 347, 750

Mundel, C.G., Pedlar, A., Baum, S.A. et al. 1995, MNRAS, 272, 355

Packham, C., Hough, J.H., Young, S. et al. 1996, MNRAS, 278, 406

Pier, E., Krolik, J. 1992, ApJ, 401, 99

Rowan-Robinson, M. 1992, MNRAS, 258, 787

Rowan-Robinson, M., Crawford, J. 1989, MNRAS, 238, 523

Schreier, E.J., Marconi, A., Axon, D.J. et al. 1998, ApJ, 499, 143

Tonry, J.L., Schechter, P.L. 1990, AJ, 100, 1794

Wilson, A.S. 1988, A&A, 206, 41

Young, S., Packham, C., Hough, J.H., et al. 1996, MNRAS, 283, L1