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The Circinus Galaxy: A starburst or AGN?

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Abstract. In the context of the unified model of Seyfert galaxies, we use observations from the literature and a radiative transfer model to investigate the near–IR to mm emission produced by the presumed torus in the Circinus galaxy, from 2μm to 1.3mm. From the infrared SED modelling, we find that the total luminosity (L_{IR}) in this wavelength range, consists of similar contributions from the torus and starburst, with a ratio of nuclear luminosity to starburst luminosity (L_{NUC}/L_{SB}) ~ 0.8.

By using a similar torus model to that of NGC1068, *but without the conical dust*, we find an upper limit to the outer torus radius of ∼12pc with a best fit of ∼2pc. The upper limit torus size estimated from the radiative transfer modelling is consistent with the 16pc torus radius estimated from near–IR imaging polarimetry of Circinus [25].

1. Introduction

Observational evidence for obscuring material in the centres of Active Galactic Nuclei (AGN) is now abundant. It is believed that the obscuring material in the innermost regions of the AGN takes the form of a dusty "torus" which blocks and absorbs part of the radiation from the active nucleus. These dusty tori play an essential role in unified theories of Seyfert galaxies and strongly support the unification models (See GH Lecture notes for a complete description of unification theories). Direct imaging of the presumed torus is technically demanding due to its (predicted) small size [3], [4], [2]. The most convincing direct evidence for a Seyfert torus comes from observations of the HCN molecule [5], which traces dense molecular gas, and near–IR imaging polarimetry [6], both of NGC1068.

The origin of the infrared continuum in a number of Seyfert 2 galaxies is clearly thermal as indicated by silicate features such as the broad absorption at 10μm [7] and the various emission features from polycyclic aromatic hydrocarbons (PAHs) which are normally associated with the presence of hot stars in a starburst environment. Dust grains, distributed in a toroidal geometry surrounding the central black hole and accretion disc, are believed to be responsible for the absorption of radiation from the central source and re–radiation of energy into longer wavelengths giving rise to the observed "IR bump" longwards of 1μm and peaking at mid–IR wavelengths [8]. The resultant radiation spectrum is dependent on the distribution of dust grain temperatures ($\leq$ 2000K) and optical depth. Two additional components can add to the IR spectra of active galaxies: galactic diffuse emission from large dust grains heated by the interstellar radiation field in the galactic disc (cirrus, $T_{large-grains} \leq 40$K) and a starburst component peaking at about 60μm.

Here, we present a model for the IR continuum emission of the Circinus galaxy which successfully fits the observations from 2μm to mm wavelengths. We constrain the size and flux of the dusty AGN torus and estimate the contribution of the starburst emission to total IR emission.

2. The Data

The continuum and PAHs data points have been compiled from a variety of sources in the literature. There is a large range of sizes in the observational apertures, from arcsec to arcminute beamsizes, equivalent to physical sizes of <5pc and >200pc (for Circinus, 1 arcsec corresponds to 20pc); whenever possible, data from the smallest available aperture were used to minimise the contribution from galactic disk emission. The data point at 2.2μm corresponds to the deconvolved non–stellar measurement as presented by Maiolino *et al.* [9] and derived from a 0.15arcsec aperture. In the mid–IR, between 3 and 20μm, the continuum data points at 3.8 and 4.8μm, are provided by Siebenmorgen *et al.* [10]. Other continuum data points over this wavelength range are from an ISO SWS spectrum presented in Moorwood *et al.* [12]. Line information for the PAH features at 3.28, 6.2, 7.7, 8.6 and 11.3μm were directly measured from the ISO SWS spectrum. The spectrum corresponding to the Si absorption feature centered at 9.7μm was taken with a 4.3arcsec aperture and provided by P. Roche [7]. The N(10.3μm) band continuum data point, is also provided by Siebenmorgen *et al.* [10] and measured through a 1.3arcsec slit. The continuum data points at 20, 30 and 40μm were taken from

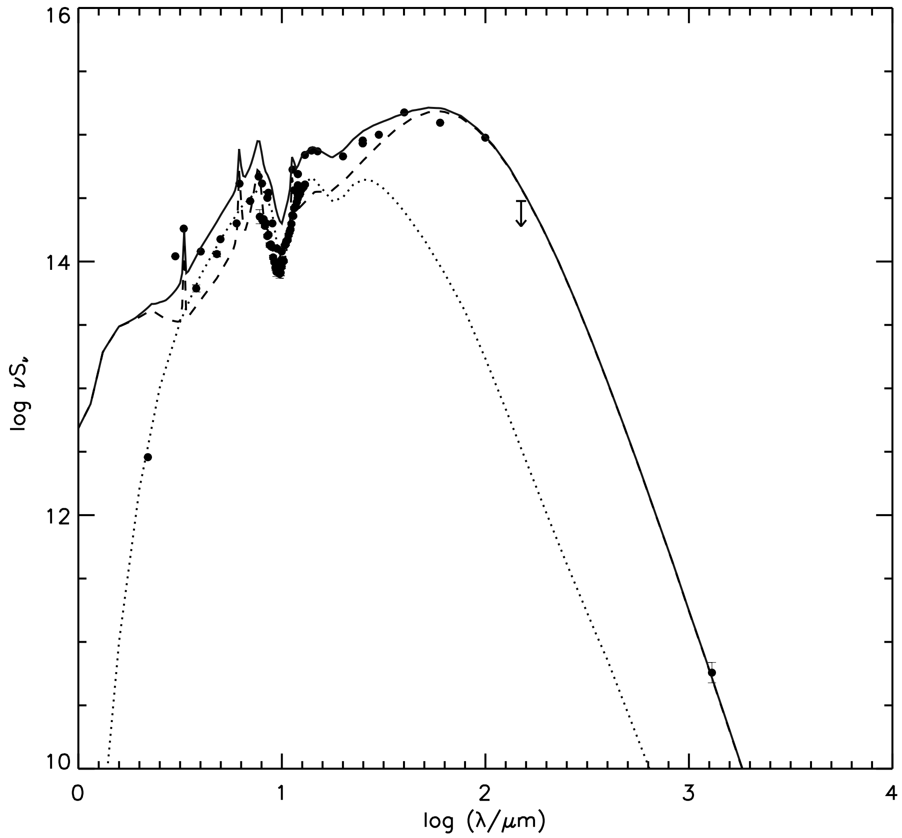

Fig. 1. IR SED for the Circinus galaxy. The SED is fitted with a starburst and a torus model. Dark circles are the observational data points. Units for νS_ν are 10^{-26}W/m^2. Dotted line corresponds to the torus component, dashed line is the starburst component and the solid line represents the total fit.

the ISO SWS spectrum and thus, nuclear emission is contaminated with emission from circumnuclear star–forming regions. The ISO SWS spectrum at 25μm agrees within 20% of the *IRAS* flux. The far–IR continuum observations were collected from the *IRAS* large aperture observations (90arcsec) at 12, 25, 60 and 100μm as reported by Moshir *et al.* [13]. The continuum data point at 150μm was taken from the analysis by Ghosh *et al.* [14] which corresponds to an aperture of 40arcsec. At millimeter wavelengths, Circinus has been detected at 1.3mm with an aperture of 23arcsec as reported by Siebenmorgen *et al.* [10]. Clearly, the large aperture observations are contaminated with light from various emission sources particularly from the extended galactic disc; thus, special care is needed when fitting the large aperture data points to the individual emission components in the radiative transfer model.

3. The General Infrared model

The model used is the radiative transfer model of Efstathiou *et al.* as described in detail in [15], [3] and [16]. This radiative transfer model has been successful in fitting the IR continuum of NGC1068 [3] and Centaurus A [2]. The proposed model for the SED of the Circinus galaxy is a combination of the following two components described below.

3.1. Torus

As concluded in [15], the most likely geometry for the obscuring material in the center of AGNs, is that of a "tapered disc". We therefore assume this geometry for the Circinus torus. As demonstrated by Efstathiou and Rowan–Robinson [17] the orientation of the plane of the system to the line–of–sight is a very important parameter when fitting the observed spectra, since only a small difference in this inclination parameter, θ_V, produces a significant variation in the emergent spectrum. Another important parameter that determines the shape of the IR continuum, is the half–opening angle of the torus, Θ. In general, these parameters are not known for most objects, but fortunately, we have a good idea of their values from spectropolarimetry [1] and IR–imaging polarimetry of Circinus [26] which gives $\theta_V \sim 40$ degrees (measured from the axis of the torus to the line of sight) and $\Theta \sim 45$ degrees. Other parameters that will affect the shape of the emergent SED spectrum are: the ratio of the inner and outer radii (r_1/r_2), the ratio of the height to the outer radius (h/r_2), the equatorial optical depth ($^{eq}A_{UV}$), the dust sublimation temperature (T_1) and the radial dependence of the density distribution $r^{-\beta}$. To take into account the effects of dust in the nuclear regions of Circinus, we assume that there is an additional extinction (i.e. in addition to that produced by the torus) equivalent to A_V=25mag.

3.2. Starburst

The radiative transfer models of starburst galaxies are described in detail in [16]. The models consider a starburst galaxy as an ensemble of optically thick giant molecular clouds centrally illuminated by recently formed stars. The stellar population is determined according to the Bruzual and Charlot [18] stellar population synthesis models. The grain model used is that of Siebenmorgen and Krügel [19] and the emission of transiently heated dust grains is calculated according to their method. In the models, the effects of multiple scattering is taken into account. The models relate the observed properties of a galaxy to its age and star formation history. These models have successfully matched the observational characteristics of M82 and other starburst galaxies [16]. To take into account the effects of dust in the starburst regions of Circinus, we extinct the starburst emission by A_V=5mag, as measured from narrow emission line ratios [20]. This is lower than the additional extinction assumed to the nucleus (section 3.1), as the starburst is expected to be outside the circumnuclear molecular bar.

4. Model fitting

The critical wavelength range for the fitting of the SED to the observational data points is likely to be where the torus and starburst components are equally important that is, in the 10–30μm region. Here, the strong absorption feature is indicative of the presence of dust in the form of silicates which are likely to be present in a dusty environment such as the torus, however, the observational beam for this data is large enough to include the star formation region. Thus, contributions from both the torus *and* starburst components are important in this wavelength range. On the other hand, given that the near–IR points are to be modelled by the torus alone (nuclear apertures), we have a strong constraint on the number of possible models to be tested for the torus. Similarly, in the long wavelength range (large aperture data points) which include the PAHs features, the starburst component dominates, and only a number of starburst models can be applied. Thus, the overall fitting procedure is much better constrained and the number of free parameters reduced once the short and long wavelength ranges are considered.

The best SED fits were obtained with a cone half–opening angle of 30 degrees. There is no requirement to include a contribution from hot dust in the torus cone, as in the NGC1068 case. In Figure 1 we show the best model for the SED of the Circinus galaxy which is the addition of the torus and starburst models. Note that the solid line (representing the total emission from the galaxy) exceeds the mid–infrared data of Roche *et al.* 1991). This is not surprising as the starburst which contributes about half of the emission is more extended that the 4arcsec aperture of Roche *et al.* [7].

Unfortunately, there is a serious lack of small aperture (nuclear) data in the range of 30–60μm. As a consequence, we are unable to rule out tori up to ~12pc although increasing the torus outer radius further would produce far too much 30–60μm flux. Future observations in this critical wavelength range, will put extra constraints on the torus model, and the torus size will be determined more accurately.

It is interesting to note in Figure 1 the overall larger contribution to the total IR emission of the starburst compared to the torus component. This is indicated by the ratio of the nuclear luminosity –torus component– to starburst luminosity –starburst component– (L_{NUC}/L_{SB}) $\sim$ 0.8 (see next section).

5. Discussion

Our SED model shows that, overall, the starburst contribution to the total IR luminosity, L_{IR} slightly dominates over the torus contribution. A direct result of this, is the relatively small size of the torus in Circinus, with a best fit of ~2pc for the outer radius. This radius size is smaller than that calculated from the near–IR imaging polarimetry modelling of Ruiz *et al.* [25] which suggests that the torus is approximately 16pc in radius, although consistent with our upper limit of ~12pc.

So far, by using the radiative transfer models of Efstathiou *et al.* we have been able to model the size of the torus outer radius for three objects: NGC1068 [3], CenA [2] and Circinus [26]. Although the statistics are small, it is interesting to note that all three AGN can be modelled with tori of very similar parameters. This suggests that, whatever the mechanism that forms these tori in an AGN–SB environment, it is such that the size of the tori scales with the luminosity of the central source but the rest of the torus parameters are *scale invariant*. For example, the hard X–ray continuum, which is considered to be a good indicator of the central source strength, indicates that the Circinus galaxy is a relatively low luminosity AGN [23], while NGC1068 is $\sim$ 100 times more powerful [24], with a torus radius ~100pc. The predicted torus radii scales as $L^{1/2}$, reflecting the fact that both objects can be fitted with very similar radiative transfer models.

Of great debate regarding the nature of the Circinus galaxy is the ratio of the AGN to starburst emission (L_{NUC}/L_{SB}), that is, the relative contribution of the torus and starburst components to the total L_{IR}. Previous predictions from IR modelling differ widely. For example, Rowan–Robinson and Crawford [8] found a 20% contribution of the nuclear component to the total L_{IR} and L_{NUC}/L_{SB} ~0.3 while this work suggests a L_{NUC}/L_{SB} of 0.8. On the other hand, from the Brα luminosity, Moorwood *et al.* [12] estimate that this ratio is perhaps as high as 9. Our result is in very good agreement with that suggested by Maiolino *et al.* [9] who estimate from K band observations a L_{NUC}/L_{SB} ratio of 0.9 for the region <200pc. Similarly, we agree with the ratio derived from the inferred ionising continuum required to produce the highly ionised IR lines suggesting a ratio closer to 1 [12]. On the other hand the large L_{NUC}/L_{SB} ratio derived by Moorwood *et al.* [12] suggests a strongly dominant AGN over the starburst. This was derived from the comparison of near–IR recombination lines in Circinus and M82. From a Brγ map [11], they assume that 50% of the recombination lines are produced in the nucleus of Circinus. However, this is likely to be an over–estimation of the strength of Brγ in the nucleus. More recently, a more accurate measurement of the Circinus nuclear recombination lines [9] has shown that only ~10% of the total recombination lines flux is produced in the nucleus of Circinus. Assuming the standard relation between Brα flux and total IR luminosity in starburst galaxies, we can determine the contribution of the starburst to L_{IR}. We find $L_{SB} \sim 8.5\times10^{9}L_{\odot}$, so $L_{NUC}/L_{SB} \sim 1.2$ for an AGN luminosity of $10^{10}L_{\odot}$. This is in good agreement with the ratio we find from the SED modelling.

Radio observations suggest that at these wavelengths, the starburst emission is the dominant component [22] and Circinus would certainly be classified as a starburst galaxy based purely on radio emission. Indeed, it is interesting to note that the FIR–radio correlation established by Helou, Soifer and Rowan–Robinson [21], which is followed by normal spiral and starburst galaxies, is closely followed by the Circinus galaxy, confirming Forbes and Norris result [22]. However, it is almost certain that this correlation is the result of large scale star–formation activity unrelated to the Seyfert activity which generates both the synchrotron radio emission and the thermal FIR emission. Given that the Circinus galaxy has strong star–formation activity on small and large scales, it is not surprising that this galaxy follows the FIR–radio correlation.

Nevertheless, there is a clear large variation in the predicted L_{NUC}/L_{SB} ratios from starburst dominated to AGN dominated, depending on the spectral range and the observational technique. The undoubted composite nature of the Circinus galaxy is shown in our IR SED model which predicts a galaxy dominated by the AGN torus at near–IR wavelengths while at far–IR to mm wavelengths the starburst activity is the dominant one.

6. Conclusions

The case of the Circinus galaxy provides strong support for the dusty torus model of active galaxies which further support the unification scheme, that is, thick dusty tori with a tapered disc geometry surrounding the central engine.

Our best fit for the outer radius size of the torus in Circinus is ~2pc, but a radius as large as 12pc can not be ruled out.

We confirm the composite nature of the Circinus galaxy, which is dominated by the AGN torus emission in the near–IR but largely dominated by starburst phenomena in the far- -IR and mm wavelengths. The L_{IR} is slightly dominated by the starburst emission and we find a ratio $L_{NUC}/L_{SB} \sim 0.8$.

For a detailed discussion of the SED modelling in the Circinus galaxy, see Ruiz *et al.* 2000b [26]

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