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Starbursts and dusty tori in distant 3CR radio galaxies

Pece Podigachoski,1⋆ Brigitte Rocca-Volmerange,2,3 Peter Barthel,1 Guillaume Drouart4 and Michel Fioc2

1 Kapteyn Astronomical Institute, University of Groningen, PO Box 800, NL-9700 AV Groningen, the Netherlands
2 Institut d’Astrophysique de Paris, Universite Pierre et Marie Curie/CNRS, 98 bis Bd Arago, F-75014 Paris, France
3 Universite Paris-SUD, F-91405 Orsay Cedex, France
4 International Centre for Radio Astronomy Research, Curtin University, Bentley, WA6102, Perth, Australia

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ABSTRACT
We present a study of the complete ultraviolet to submillimetre spectral energy distributions (SEDs) of 12 3CR radio galaxy hosts in the redshift range $1.0 < z < 2.5$, which were all detected in the far-infrared by the Herschel Space Observatory. The study employs the new spectro-chemical evolutionary code PÉGASE.3, in combination with recently published clumpy active galactic nuclei (AGN) torus models. We uncover the properties of the massive host galaxy stellar populations, the AGN torus luminosities, and the properties of the recent starbursts, which had earlier been inferred in these objects from their infrared SEDs. The PÉGASE.3 fitting yields very luminous (up to $10^{13}$ $L_{\odot}$) young stellar populations with ages of several hundred million years in hosts with masses exceeding $10^{11}$ $M_{\odot}$. Dust masses are seen to increase with redshift, and a surprising correlation – or better upper envelope behaviour – is found between the AGN torus luminosity and the starburst luminosity, as revealed by their associated dust components. The latter consistently exceeds the former by a constant factor, over a range of one order of magnitude in both quantities.

Key words: galaxies: active – galaxies: evolution – galaxies: high-redshift – galaxies: starburst.

1 INTRODUCTION

The episodic accretion of matter on to supermassive black holes (SMBH), which are nowadays assumed to exist in the central regions of almost all massive galaxies in the Universe, results in phenomena known as active galactic nuclei (AGN). Because of the interaction with their host galaxies, primarily exhibited via negative and/or positive feedback processes, AGN are essential elements – or phases – in the evolution of galaxies through cosmic time. Particular attention in studies of galaxy evolution is paid to the early epoch $1 < z < 3$, which is the time when both the stellar bulges of galaxies and their associated black holes went through peak growth (Alexander & Hickox 2012; Heckman & Best 2014).

A small fraction of AGN are characterized by strong radio emission, which is produced by the powerful radio-jets and radiolobes driven by the growth of the black hole. The most powerful radio-loud AGN are the so-called FRII sources (Fanaroff & Riley 1974). By virtue of their huge radio luminosities, these sources were historically used in searches for the most distant objects in the Universe (Roettgering et al. 1994; Stern & Spinrad 1999). While no longer being the highest redshift holders, radio-loud AGN (and their hosts) have remained central in studies of the interplay between AGN and star formation (SF) activity in massive galaxies in the early Universe (see Miley & De Breuck 2008, for a review). The reasons are straightforward: high-z radio-loud AGN are powerful AGN (Haas et al. 2008; De Breuck et al. 2010; Dicken et al. 2014), and their hosts are among the most massive galaxies in the Universe (Best, Longair & Roettgering 1998a; Seymour et al. 2007) often showing prodigious levels of SF activity (Archibald et al. 2001; Reuland et al. 2004; Drouart et al. 2014; Tadhunter et al. 2014; Podigachoski et al. 2015a). From the sharp cut in the Hubble K-band diagram, and using elliptical scenarios corrected for evolution and cosmology, Rocca-Volmerange et al. (2004) estimated a maximum stellar mass of $10^{12}$ $M_{\odot}$ for $1 < z < 4$ objects.

Additionally, radio-loud AGN are often used in unification studies. Within the framework of the unified model of radio-loud AGN (Barthel 1989), FRI radio galaxies (RGs, type 2) and radio-loud quasars (type 1) are assumed to belong to the same parent population, and can be unified based on orientation (see Antonucci 2012, for a recent review). Central to this model is the AGN torus, a region rich in molecular gas and dust perpendicular to the radio source axis, obscuring the accretion disc and the broad-line region along a substantial range of viewing angles (e.g. Drouart et al. 2012). In
the case of RGs, the torus acts like a natural coronograph, blocking most of the ultraviolet (UV)/optical light emitted due to the AGN activity (e.g. Wilkes et al. 2013) and – in contrast to quasars – enabling detailed studies of the stellar populations of the AGN host galaxy.

Originally selected at low radio frequencies (178 MHz), the landmark Revised Third Cambridge Catalogue of Radio Sources (hereafter 3CR; Spinrad et al. 1985) contains some of the brightest radio-loud AGN at all redshifts. The $z > 1$ double-lobed (FRII) RGs and quasars in the 3CR sample almost universally accrete at high Eddington rates, i.e. in quasar-mode (e.g. Best & Heckman 2012), resulting in an unbiased sample, free of any of the low-power AGN often found at lower redshifts ($z \sim 0.5$). The $z > 1$ part of this sample has been observed with virtually all space-based telescopes (Best, Longair & Roettgering 1997; Haas et al. 2008; Leipski et al. 2010; Wilkes et al. 2013; Chiaberge et al. 2015), including the Herschel telescope (Barthel et al. 2012; Podigachoski et al. 2015a).

Using primarily Spitzer and Herschel broad-band photometry, Podigachoski et al. (2015a) decomposed the rest-frame infrared (IR) spectral energy distributions (SEDs) of the complete $z > 1$ 3CR sample into AGN- and SF-related components, adopting for the latter a typical modified blackbody with a fixed dust emissivity index. Compared to studies of other radio-loud AGN in the high-$z$ Universe (e.g. Drouart et al. 2014), Podigachoski et al. (2015a) found a somewhat higher Herschel detection fraction, with about half of their sample objects detected in at least three Herschel bands, indicating star formation rates (SFRs) of several hundred solar masses per year. Such prodigious SFRs, at the level of those of typical submillimetre galaxies at similar redshifts, were found despite the powerful AGN activity which often dominates the IR luminosities of the 3CR objects, ruling out uniform quenching of SF and providing tentative evidence for jet-triggering of SF (Podigachoski et al. 2015a). Adopting a modified blackbody component to account for the emission of the SF-heated dust provides robust estimates of the temperature and the mass of this cold dust in AGN hosts; however, it yields no information on the mass, age, and/or metallicity of the (young) stellar component which powers the dust emission in the rest-frame far-infrared (FIR). Such information, particularly for AGN hosts which are not completely enshrouded by dust, can be robustly obtained by also considering the unattenuated part of the stellar continuum due to the young stars. Furthermore, by only exploring SEDs beyond 1 $\mu$m in the rest frame of the objects, Podigachoski et al. (2015a) do not consider the evolved stellar populations in the hosts of 3CR AGN, which are expected to peak at about 1 $\mu$m in the rest frame.

Here, we extend the work of Podigachoski et al. (2015a) by studying the rest-frame UV (UV) to submillimetre (submm) SEDs of 12 $z > 1$ 3CR RG hosts, identifying the emissions from the past and recent stellar populations and from the AGN torus, with the goal to constrain the physical properties of these stellar populations. We use the new spectro-chemical evolutionary code PÉGASE.3 (Fioc & Rocca-Volmerange, in preparation), which follows the masses of stars, gas and dust, determines the attenuation of stellar emission by grains in H II regions and the diffuse interstellar medium (ISM), and consistently computes the emission of the latter. Galaxy templates computed with PÉGASE.3 were earlier used by Rocca-Volmerange et al. (2013), who performed a pilot study of two distant ($z = 3.8$) RGs selected for their small AGN contributions. Coupling PÉGASE.3 templates with smooth torus models by Fritz, Franceschini & Hatziminaoglou (2006), Drouart et al. (2016) recently extended this pilot study to a sample of 11 more powerful RGs from the $1 < z < 4$ sample of Drouart et al. (2014). Here, we use the latest torus models in the literature (Siebenmorgen, Heymann & Efstathiou 2015) in a study of a dozen well-known 3CR RGs, also aiming to test the different AGN torus formalisms. We consider only RGs, but maintain the view that most results obtained for this AGN class are applicable also for radio-loud quasars within the unified model of radio-loud AGN (e.g. Podigachoski et al. 2015b).

This paper is organized as follows. In Section 2, we present the sample used in this work, and the observational data which we use as input for our SED fitting approach. In Section 3, we provide overview of the PÉGASE.3 model predictions including a coherent dust emission, and of the adopted library of torus models. The results, including the best-fitting SEDs of each sample object, are presented in Section 4, and discussed in Section 5. We conclude this paper with a brief summary (Section 6). The appendix contains details on the observational data for each object studied in this work.

2 SAMPLE SELECTION AND DATA

The RGs studied in this work belong to the 3CR (Bennett 1962; Spinrad et al. 1985). Being selected due to their steep-spectrum radio emission from their radio-lobes, these objects are some of the most powerful AGN at any redshift in the Universe. The sample studied in this work is a subset of the complete high-$z$ ($z > 1$) catalogue of 3CR RGs, which contains a total of 37 RGs (Spinrad et al. 1985). The highest redshift object is 3C 257 at $z = 2.474$, while all other sources are at redshifts $1 < z < 2$.

Decomposing the SEDs of RGs into stellar and AGN-related components requires observations at the mid-infrared (MIR). The complete high-$z$ 3CR sample has been observed at six different bands at wavelengths between 3.6 and 24 $\mu$m with all Spitzer imaging instruments (Haas et al. 2008). Given that almost all RGs have been detected with all Spitzer instruments at good signal-to-noise ratios, the Spitzer photometry does not introduce any selection effects. We note, however, that such effects are introduced when selecting objects which have been detected in the rest-frame FIR and UV/optical bands, as described below.

A crucial step forward in understanding the properties of the high-$z$ 3CR sample has recently been provided by Herschel imaging, using both imaging instruments (PACS at 70 and 160, and SPIRE at 250, 350, and 500 $\mu$m). Full details on the data reduction and photometry of the 3CR sample are provided by Podigachoski et al. (2015a). As shown in that paper, the typical temperature of the cold dust in 3CR hosts is about 40 K, which means that the peak due to the dust-reprocessed young stellar emission occurs at around 70 $\mu$m. To constrain this peak, we require that each RG is detected in at least one photometric band at rest-frame wavelength greater than 70 $\mu$m, which, given the redshift of our RGs, requires that the objects are detected in the SPIRE 250 $\mu$m band.\(^1\) This is in fact the main criterion we impose when selecting the RGs for this work, and this criterion is only relaxed in two cases, 3C 210 and 3C 356, because despite them being detected in only the two PACS bands, their sufficiently low redshift ensures that the PACS 160 $\mu$m band probes emission beyond the IR peak. 15 RGs satisfy this selection criterion. Clearly, selecting the Herschel-detected RGs means that our work features only the most prodigiously star-forming 3CR RGs. However, as pointed out by Podigachoski et al. (2015a), the objects not detected with Herschel might still actively form stars, though at a significantly lower level.

\(^1\) Note that all objects with a robust SPIRE 250 detection are also detected in both PACS bands.
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In addition to powering the dust-reprocessed emission in the FIR, young stars – when not attenuated – also emit strongly in the UV/optical. Furthermore, the evolved stellar populations produce stellar continuum radiation which peaks in the optical/near-infrared (NIR; Rocca-Volmerange et al. 2013). Both considerations render UV-to-NIR observations crucial to our SED study of RGs. A major study of the properties of \( z \approx 1 \) 3CR RGs was performed by Best et al. (1997), whose work is the source of most NIR data and about half of the UV/optical data used in our work. More UV/optical observations with the improved Hubble Space Telescope (HST) were recently obtained as part of an HST SNAPSHOT programme (Chiaberge et al. 2015; Hilbert et al. 2016). To better constrain the ages of the stellar populations, we require that each RG has at least two photometric observations, one on either side of the 4000Å break. This selection criterion limits the 15 Herschel-detected objects to 13, which can be grouped as follows: 8 have at least two HST and one NIR observation (mainly provided by Best et al. 1997), and 5 have only two HST observations (mainly provided by Chiaberge et al. 2015) and no NIR observations. The prominent emission lines seen in the UV/optical spectra of high-\( z \) RGs (e.g. McCarthy 1993; Best, Röttgering & Longair 2000), including but not limited to C\( \text{II} \), Ne\( \text{v} \), O\( \text{II} \), H\( \beta \), O\( \text{III} \) and H\( \alpha \) may have an important contribution (\( \approx 30 \) per cent) to the total flux measured in broad-band filters; these line fluxes have been subtracted based on optical spectra as explained in the corresponding reference papers (Best et al. 1997; Hilbert et al. 2016).

Hence, the final sample studied in this work contains 12 well-known type 2 AGN of the 13 RGs which satisfy both selection criteria: we remove 3C 119 from the subsequent analysis, because it has been shown that it is an object with a quasar-like NIR/MIR SED (see Podigachoski et al. 2015b). The location of the sample in the radio luminosity–redshift plane is shown in Fig. 1. As shown in that figure, the selected RGs are homogeneously distributed in redshift. The main parameters of the final sample addressed in this work are summarized in Table 1. Tables listing the details of the available photometry used for the fitting for each of these RGs are presented in the appendix.

In addition to the photometric observations presented above, some 3CR RGs with redshifts \( z < 1.4 \) have been observed in spectroscopic mode with the IRS spectrograph on Spitzer (Leipski et al. 2010). The availability of such spectra is not a selection criterion in our work: the spectra are merely used to confirm that the torus models which we apply account well for the MIR photometry of RGs, and that the disentangling of AGN and young stellar components in the important MIR/FIR transition region is reasonably robust. Given the spectral window covered by the IRS spectrograph, between 19.5 and 36.5 \( \mu \text{m} \), and the redshift range of the 3CR RGs given above, the Spitzer spectra often contain both low- and high-excitation MIR emission lines (e.g. Ne\( \text{II} \), Ne\( \text{v} \), Ne\( \text{III} \)), the 11.3 \( \mu \text{m} \) line from polycyclic aromatic hydrocarbon (PAH) features, and the 9.7 \( \mu \text{m} \) silicate feature (Leipski et al. 2010). To include the spectroscopic information to the SED analysis, we measure flux densities at three artificial broad-band filters centred at 27, 30, and 33 \( \mu \text{m} \). The RGs which have Spitzer spectra are: 3C 266, 3C 324, 3C 356, and 3C 368 (see Table 1).

Finally, some objects from our final sample also have submm (850 \( \mu \text{m} \)) observations. Given that our high-\( z \) 3CR RGs are exclusively steep-spectrum radio sources, any synchrotron emission from the radio-lobes can safely be neglected, and in practice, these observations probe the Rayleigh–Jean tails of the thermal dust continuum emission (see e.g. Haas et al. 2006; Podigachoski et al. 2015a).

### Table 1. The 12 objects selected from the complete \( z > 1 \) 3CR sample of radio galaxies and studied in this work.

<table>
<thead>
<tr>
<th>Name</th>
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<th>( \log(L_{178\text{MHz}}(\text{WHz}^{-1})) )</th>
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</tr>
<tr>
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<td>1.82</td>
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</tr>
<tr>
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<td>2.47</td>
<td>29.7</td>
</tr>
<tr>
<td>3C 257</td>
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<td>29.1</td>
</tr>
<tr>
<td>3C 297</td>
<td>1.41</td>
<td>29.1</td>
</tr>
<tr>
<td>3C 305.1</td>
<td>1.13</td>
<td>29.0</td>
</tr>
<tr>
<td>3C 324*</td>
<td>1.21</td>
<td>29.2</td>
</tr>
<tr>
<td>3C 356*</td>
<td>1.08</td>
<td>28.9</td>
</tr>
<tr>
<td>3C 368*</td>
<td>1.13</td>
<td>29.0</td>
</tr>
<tr>
<td>3C 454.1</td>
<td>1.84</td>
<td>29.4</td>
</tr>
<tr>
<td>3C 470</td>
<td>1.65</td>
<td>29.3</td>
</tr>
</tbody>
</table>

2 The Best et al. (1997) HST observations were later re-analysed by Inskip, Best & Longair (2006), who extracted the photometry of the 3CR RGs in 4 arcsec apertures as opposed to the 9 arcsec (diameter) apertures used by Best et al. (1997). To compute colours at the exact same filters for each RG, in most cases, Inskip et al. (2006) relied on interpolations based on observations in other nearby filters. To avoid the additional uncertainty associated with this step, we choose the Best et al. (1997) measurements despite the fact that some of our objects may have some contamination from nearby objects within the larger aperture (see Section 5.4).

3 Leipski et al. (2010), in fact, studied the complete sample of 3CRR radio-loud AGN at the redshift range \( 1 < z < 1.4 \), but because the 3CRR catalogue is a subsample of the parent 3CR catalogue studied in this work, the few 3CR RGs in this redshift range not belonging to 3CRR do not have Spitzer spectroscopy.

### 3 Models and Templates

The templates used in this work are built with the help of two models: the evolutionary synthesis code PEGASE.3 (Fioc &
Rocca-Volmerange, in preparation), and the AGN torus model by Siebenmorgen et al. (2015). Both models use Monte Carlo simulations for solving the radiative transfer equations.

3.1 PÉGASE.3 models

PÉGASE.3 predicts the attenuated star and gas emission, and the coherent dust emission from the attenuation, coherently transferred through the diffuse ISM and star-forming regions. Built as a flexible tool, PÉGASE.3 provides an extensive range of choices in terms of SFRs, initial mass functions, and inflow or outflow rates to mimic the galaxy evolution for starbursts and various spectral types over a large-redshift range. It tracks the chemical ISM enrichment of specifically the elements C and Si, plus O, Fe, N, and other metals, from which dust mass grows. At any wavelength, the code sums the contributions of the stellar photospheric emission, nebular continuum and the dust emission of the heated grains. Destruction and accretion dust phases are considered using classical Draine continuum and the dust emission of the heated grains. Destruction and accretion dust phases are considered using classical Draine models and specific modelling (Dwek 1998). Through Monte Carlo simulations of radiative transfer, the attenuation (absorption and scattering) and dust re-emission (including stochastic heating) are predicted for various geometries (slab, spheroids, bulges + discs). The main difference of PÉGASE.3 with most other models is the coherence in metal enrichment from the stellar ejecta derived from the adopted SF law. Extended to a large coverage of wavelength domain and respecting energy conservation, it is used in place of extinction laws or any UV–FIR relations. Galaxy scenarios by type are defined with a limited number of free parameters (SFR, inflow, outflow and initial mass function) to be compatible with the local galaxy colour–colour distribution (Tsalmantza et al. 2012). The detailed documentation (at http://www2.iap.fr/pegase) provides the possibility to propose new scenarios among those derived from semi-analytic models or numerical simulations. As 3CR RG hosts are expected to be massive ellipticals occasionally undergoing bursts of SF, we consider here only starburst and early-type scenarios, as used by Rocca-Volmerange et al. (2013) and Drouart et al. (2016).

3.2 AGN torus models

The high-ζ 3CR RGs are demonstrably powerful emitters in the rest-frame MIR (Haas et al. 2008; Podigachoski et al. 2015a), where thermal emission from the AGN torus dust is the most dominant emission process. The physical origin of and the distribution of dust within the AGN torus are hotly debated issues in the literature. The two main families of models in the literature are the smooth models (e.g. Fritz et al. 2006), whereby dust is distributed homogeneously throughout the torus, and the clumpy models (e.g. Nenkova et al. 2008; Hönig & Kishimoto 2010), whereby dust is located in individual dusty clouds filling the torus. A number of photometric and spectroscopic studies have been performed aiming to pin down the relevant physical parameters within a given formalism, yet the best evidence (albeit from a small number of nearby objects) comes from MIR interferometric studies (e.g. Hönig et al. 2013, and references therein).

In this work, we adopt the models presented by Siebenmorgen et al. (2015), whose formalism includes both a homogeneous disc of gas and individual dust clouds randomly distributed throughout the torus. The five free parameters of these models are: (i) viewing angle (nine values), (ii) inner torus radius (five values), (iii) volume filling factor of clouds (four values), (iv) optical depth of clouds (four values), and (v) optical depth of disc mid-plane (five values), which results in a library of 3600 unique torus models. Given the dense environment in circum-nuclear regions, the Siebenmorgen et al. (2015) models adopt fluffy dust grains, a choice resulting in stronger FIR and submm emission compared to other clumpy models, but also a more pronounced NIR emission because the larger (than standard ISM) fluffy grains can survive much closer to the AGN. This, together with the additional material in the innermost region of the torus provided by the homogeneous disc and the dust clouds in the ionization cones of the AGN, naturally reproduces the NIR bump seen in some RGs. Note that given the limited photometric data in the MIR in this work, we cannot study the torus in detail, and we stress that our goal is to simply isolate the AGN-powered emission from the stellar emission.

3.3 SED fitting procedure

Following the approach by Drouart et al. (2016), synthetic libraries of early-type galaxy and starburst plus AGN templates are built with a variety of parameters over large ranges. The free parameters for the early-type galaxy templates include the normalization and the age of the stellar component, and the ones for the starburst templates include the initial metallicity in addition to the age and normalization of this stellar component. More than 104 templates are tested for comparison to the global observed SEDs. The instantaneous starburst (see Rocca-Volmerange et al. 2013) is preferred to test the most powerful emitters in the FIR: its parameters are a Kroupa, Tout & Gilmore (1993) initial mass function, and no outflow or infall. As described by Drouart et al. (2016), the AGN templates are added to each starburst template as a relative contribution at 20 μm, using a grid of values ranging between dominant to negligible AGN contribution at this particular wavelength. Observations are compared to the sum of normalized SED templates by a χ2-minimization procedure (Le Borgne & Rocca-Volmerange 2002) on the largest wavelength coverage, providing the best fit of the bolometric luminosity. The calibration factor is derived from the global best-fitting synthetic SED compared to the observations, which is then applied to all normalized PÉGASE.3 outputs (e.g. masses, luminosities, etc.)

4 RESULTS

In this section, we discuss the overall successes and limitations of the SED fitting approach, and the results obtained from the best-fitting SEDs. The best-fitting SEDs are presented in Figs 2 and 3, and details on the observations of 12 individual RG hosts are provided in the appendix. We mainly focus on the physical properties of the young stellar component obtained from the best fits, and the possible link between its IR luminosity and that of the AGN torus component. In addition to the IR luminosity, which is computed by integrating the young stellar component’s SED from 1 to 1000 μm, these properties include the age and mass of young stars, and the mass of dust which has been produced during the evolution of the starburst. We also report the stellar masses, ages, and the bolometric luminosities (integrating from 0.09 to 1000 μm) of the evolved stellar component. All results are tabulated in Table 2, and some are plotted in Fig. 4.

4.1 Spectral energy distributions

As shown by Rocca-Volmerange et al. (2013), Rocca-Volmerange, Drouart & De Breuck (2015) and by Drouart et al. (2016), the presence of different stellar populations in RG hosts and their strongly
Figure 2. The best-fitting UV-to-submm spectral energy distributions (SEDs) of the 3CR radio galaxies studied in this work. The observed SEDs (in units $\lambda F_\lambda$) are shown with red symbols. The components combining to yield the total SED (black) are as follows: old stellar component modelled with PEGASE.3 (orange), young stellar component modelled with PEGASE.3 (blue), and AGN-powered torus component (green) from the library of Siebenmorgen et al. (2015). Overplotted in magenta are the Spitzer IRS spectroscopic observations, available for selected sources. Zoom-ins of the regions probed by these spectra are shown in Fig. 3.
of some 3CR RGs (e.g. Podigachoski et al. 2015a) is also well reproduced with the Siebenmorgen et al. (2015) library of torus models. In some cases, the strong AGN activity responsible for this NIR bump can outshine the 1 μm peak usually associated with the evolved stellar population in RGs (e.g. 3C 257).

While the adopted three-component approach successfully reproduces the observed SEDs of all RGs, it may not give satisfactory physical results for some particular objects. This mainly concerns the estimated ages of the old stellar components associated with 3C 256, 3C 266, and 3C 368, which, as discussed below, are estimated to be the youngest throughout the sample. As argued by Best et al. (1998a, for 3C 266 and 3C 368) and Simpson et al. (1999, for 3C 256), these sources are among the ones with the strongest alignment effects, and as such, we suspect a significant non-stellar contribution to their UV/optical SEDs. However, including yet another spectral component to the radio galaxies’ SEDs, or treating some of the UV/optical flux as contributed by direct AGN emission and/or scattered AGN light is outside the scope of this work. Nevertheless, the results obtained for these sources (as indicated below) should be treated with care (see for instance Simpson et al. 1999, for a more detailed analysis of the optical SED of 3C 256). The case for a non-stellar contribution is further discussed in Section 5.4.

4.2 The young stellar component

When modelling the young stellar component (in the following, interchangeably referred to as the starburst), we use the extreme case of an instantaneous burst of SF (Rocca-Volmerange et al. 2013). Adopting such a formalism means that the starbursts in our work are by design in the post-starburst phase (SFR is equal to zero), where only the prescriptions from stellar evolution govern, among others, the production of dust grains and the overall SED shape. As expected from the robust Herschel detections of the objects in our sample, integrating these SEDs from 1 to 1000 μm yields IR starburst luminosities in excess of $10^{12} \, L_\odot$ (Fig. 4a), which puts them in the domain of ultraluminous infrared galaxies (ULIRGs; Sanders & Mirabel 1996).

Table 2 and Fig. 4(b) show that the starbursts in the host galaxies of our 12 $z > 1$ 3CR objects are massive ones, with estimated stellar masses well above $3 \times 10^{10} \, M_\odot$ in all cases, and that they amount to $\sim 20$–$\sim 50$ per cent of the total stellar mass of the systems. An exception to this trend is the host of 3C 470, wherein the young stellar component contains about 65 per cent of the total stellar mass. Given that 3C 470 is one of the objects with the highest redshifts, and the fact that the young stellar component amounts to about 50 per cent of the total stellar mass of the host of 3C 257 (redshift record holder in the 3CR sample), these objects could also be supporting the view that their hosts are still going through the process of formation, with a significant amount of stellar mass yet to form. The stellar mass (and consequently the dust mass) of the starburst on average increases when going to high redshift, which is explained in terms of the selection effect introduced by the Herschel detections.

One of the main results from our work is the relatively evolved age of the starburst, which we uniformly find to be greater than 100 Myr across all objects (Fig. 4c). While the uncertainty in the
Table 2. Best-fitting physical parameters obtained from spectral energy distribution fitting. The two fits for 3C 256 obtained with and without the UV/optical photometric data (see Section 5.4), are denoted with superscripts (a) and (b), respectively. Columns represent the following: (1) object name; (2) bolometric luminosity of the evolved (old) stellar component; (3) infrared (1–1000 μm) luminosity of the young (starbursting) stellar component; (4) infrared (1–1000 μm) luminosity of the AGN torus component; (5) stellar mass of the old stellar component; (6) stellar mass of the young stellar component; (7) dust mass of the young stellar component; (8) age of the old stellar component; (9) age of the young stellar component; (10) metallicity of the old stellar component; and (11) initial metallicity of the young stellar component.

<table>
<thead>
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<th>Name</th>
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<th>$M_{\text{stellar, old}}$</th>
<th>$L_{\text{young}}$</th>
<th>$M_{\text{stellar, young}}$</th>
<th>$L_{\text{torus}}$</th>
<th>$M_{\text{dust, torus}}$</th>
<th>Ageold (Myr)</th>
<th>Ageyoung (Myr)</th>
<th>Zold</th>
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<td>350</td>
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Age estimates is at best a factor of few, the best fits strongly favour relatively evolved starbursts, allowing – not surprisingly – sufficient time for the process of stellar evolution to generate a dust content of the order of $10^8$ $M_\odot$ (see Fig. 4d).

4.3 The AGN component

Recall that the high-$z$ 3CR RGs are powerful emitters in the mid-to-far infrared domain (rest-frame wavelengths 5–40 μm; Haas et al. 2008; Podigachoski et al. 2015a). The thermal continuum emission at these wavelengths is from the AGN-heated dust in the torus, which clearly dominates over the starburst emission following the diagnostics defined by Brandl et al. (2006). Similarly, considering the emission at 20 μm, which is the wavelength domain used by Drouart et al. (2016) to link the AGN torus to the starburst component, we find that the torus emission is, on average, an order of magnitude stronger than that of the starburst at this wavelength domain.

Quantifying the different physical parameters associated with the Siebenmorgen et al. (2015) torus library is a challenging task given the small number of broad-band MIR photometric data available, therefore we only address the torus luminosity which is calculated from the best-fitting model as described above. Nevertheless, when considering all 12 objects studied here, we find that the viewing angles of the tori are always larger than 50° (consistent with these objects being radio galaxies), the cloud volume filling factors are generally large (about 80 per cent), and the inner radii of the tori are typically smaller than about 0.25 pc, which means that the sizes of the tori themselves are smaller than about 40 pc (Siebenmorgen et al. 2015). Moreover, the optical depths of clouds avoid the extreme values in the associated parameter space, whereas the optical depths of the tori’s disc mid-plane exhibit no preferential values.

The AGN torus luminosity is plotted in Fig. 4(a). Like the luminosity of the young stellar component, it ranges between $10^{12}$ and $10^{13} L_\odot$, but is systematically lower than that of the young stellar component. Interestingly, the AGN torus luminosity appears to trace well the luminosity of the young stellar component across the entire redshift range, which is better visualized in Fig. 5. The observed trend that higher starburst luminosities trace higher torus luminosities, based on the results obtained from the SED fitting, is an intriguing one, and we return to this point in Section 5.2.

4.4 The evolved stellar component

The template representing the evolved stellar population is, in many cases, well constrained by the NIR and the shortest wavelength Spitzer data, often clearly showing the 1 μm peak due to evolved stars in the hosts of 3CR sources (Rocca-Volmerange et al. 2013). Hence, one of the more robustly estimated physical properties in this work is the stellar mass of the evolved stellar population. As shown in Fig. 4(b), this mass is of the order of $10^{11} M_\odot$ and almost always dominates the stellar mass content of the 3CR host galaxies. While undoubtedly being massive, the 3CR RG hosts appear to be less massive than the most massive elliptical galaxies ($10^{12} M_\odot$) corresponding to the brightest luminosity limit of the Hubble K-band diagram (Rocca-Volmerange et al. 2004). Using simple assumptions to subtract the young stellar and non-stellar contributions to only the optical and NIR photometry of the 3CR host galaxies studied in this work, Best et al. (1998a) estimated their stellar masses to be between a factor of 2 and 4 more massive compared to our estimates. The availability of Herschel data which better constrain the contribution of young stars in the optical likely explains our somewhat lower stellar mass estimates compared to those by Best et al. (1998a). A factor of 4 larger stellar masses for a few of our objects are also reported by Zirm, Dickinson & Dey (2003) and Targett et al. (2011), but these numbers are uncertain, given that these studies are based exclusively on K-band photometry.

Less constrained is the age of this mature stellar population, which, for about half of the objects in this work, is in the range of a few billion years (see Fig. 4c). The evolved stellar populations of these objects are consistent with being formed at high redshift and evolving passively to the redshift of observation. For the remaining objects, a somewhat lower age (between 0.5 and 1 Gyr) is preferred, and at least some of these are objects for which a contribution from an AGN component cannot be ruled out, so that the sum of an old and a young stellar component is not sufficient for a realistic fit of the observed SED in the UV/optical domain. An extreme example of this is 3C 256, which has both a stellar mass and age...
of the evolved population an order of magnitude lower than the corresponding properties of the other objects (see details below and discussion by Simpson et al. 1999). Another, more typical, example is 3C 368 (see appendix for details), which is an object for which the likely AGN contribution leads to lower estimates of the age of the evolved stellar population. For such objects, the age of this stellar population should be treated as an absolute lower limit.

The luminosity of the evolved stellar component is typically above $10^{11} L_\odot$ and is on average an order of magnitude lower than that of either the AGN torus or the young stellar population. Most of the light in the 3CR radio galaxy hosts evidently is absorbed and re-emitted by dust at longer wavelengths.

5 DISCUSSION

5.1 AGN torus models

Prior to this work, Drouart et al. (2016) analysed the UV-to-submm SEDs of a sample of $1 < z < 4$ radio galaxy hosts using templates based on the PEGASE.3 models, and the Fritz et al. (2006) library of smooth torus models. We briefly compare the results obtained for two objects, 3C 368 and 3C 470, for which much of the same input data are used in both studies. Considering the best-fitting SEDs of these two objects, Drouart et al. (2016) found that the rest-frame wavelength domain between 10 and 50 $\mu$m is dominated by the starburst emission, whereas we find that the emission in this domain is largely dominated by the torus emission. This most striking difference is a direct consequence of the adoption of the Siebenmorgen et al. (2015) models in the current work, which results in overall somewhat better fits to the Herschel photometry. We refrain from discussing the physical properties of the tori themselves, but we maintain that the Siebenmorgen et al. (2015) models also provide excellent fits to the MIR photometric, and more importantly, spectroscopic observations of the 3CR radio galaxies (Figs 2 and 3). As a result, we find significantly higher torus luminosities and older starbursts, because the strong IR torus emission associated with the clumpy models allows the peak of the starburst to move to longer wavelengths. The older starbursts, in turn, emit less extreme-UV radiation, allowing the old stellar components to account for more of the emission in this domain, hence resulting in younger

6 The input Herschel flux densities are marginally different, whereby we use the photometry by Podigachoski et al. (2015a) and Drouart et al. (2016) used than by Drouart et al. (2014).
5.2 The starburst–torus connection

The possible link between the black hole and SF activity in distant galaxies is largely debated in the literature, with a number of studies involving Herschel observations reporting either no/weak or very strong correlation between these two processes (see reviews by Hickox et al. 2014; Lutz 2014). In general, authors who find strong correlations (e.g. Netzer 2009; Bonfield et al. 2011) suggest that such correlations arise naturally given that both processes are being fuelled by the same material, possibly of origins external to the AGN host galaxy.

5.3 Age effect

High-resolution radio imaging provides a unique opportunity of measuring the lobe-to-lobe distance in RGs. Assuming a typical

\footnote{In the case of 3C 305.1 and 3C 454.1, whose observed SEDs might also be consistent with a sum of an evolved stellar and torus component, the correlation as presented would not necessarily hold.}
adams
ACKNOWLEDGEMENTS

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REFERENCES

Bennett A. S., 1962, MmRAS, 68, 163

6 CONCLUSIONS

We studied the UV-to-submillimetre broad-band SEDs of a sample of 12 Herschel-detected 3CR radio galaxies covering the redshift range 1 < z < 2.5, using stellar templates produced by the evolutionary code pÉSAGE.3 and state-of-the-art templates describing the emission from AGN-heated dust in the torus. We find that the observed photometric SEDs, and in four objects also the Spitzer spectra, are in most cases well represented by a three-component model, which, in addition to strong AGN torus emission, includes both an evolved and massive stellar component (1 Gyr or older) and a starburst, confirming previous studies in the literature. The best-fitting SEDs yield relatively evolved (~100 Myr or older) extremely massive starbursts which contain 20–50 per cent of the stellar mass of the systems, with IR luminosities systematically larger than those of the AGN torus component. The observed correlation between these two luminosities is intriguing, but remains to be confirmed with a more robust analysis based on statistically larger samples of radio galaxy hosts.

Figure 9. Fitting the spectral energy distribution of 3C 256 using all available photometric data listed in Table A3 (upper panel) and only data beyond K band (lower panel). The lines and the symbols are identical as in Fig. 2. While the physical properties estimated from the AGN and young stellar component are similar in both scenarios, those from the evolved stellar component are strikingly different (see the text for more details), and clearly incorrect in the upper SED fit.

population and a torus model) could also be considered for objects in which the starburst contributes only at the longest Herschel bands. Such a systematic study could also shed more light on the recently proposed idea of SMBH growth through accretion of supernova remnants accumulated along the SF histories of RG hosts (Rocca-Volmerange et al. 2015).
APPENDIX A: NOTES ON INDIVIDUAL SEDS

3C 210 – 3C 210 has only two strong Herschel detections, however, its redshift of $z = 1.17$ ensures that the PACS 160 μm band probes emission beyond 70 μm, hence it is included in our sample.

3C 256 – This is one of the objects in which the alignment effect in the UV/optical is particularly pronounced (see for example Simpson et al. 1999). For a complete discussion on this issue, we refer the reader to Section 5.4, and in particular to Fig. 9. Note that by excluding the UV/optical photometric data in the revised fit in Fig. 9, 3C 256 technically no longer satisfies the selection criteria explained in Section 2.

3C 257 – This is the highest redshift ($z = 2.47$) object in both our sample and in the complete $z > 1$ CR radio-loud sample.

Table A1. Table of photometric data used to fit the spectral energy distribution of 3C 068.2. The UV/optical data presented are emission-line-corrected, as explained in the relevant references provided. Aperture sized used for the photometry can also be found in the same references. References: (1) Best et al. (1997), (2) Haas et al. (2008), (3) Podigachoski et al. (2015a).

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3C 266 – For this object, Inskip et al. (2006) computed the UV/optical and NIR photometry using apertures of 4 arcsec in diameter (as opposed to that of 9 arcsec used by Best et al. 1997). We applied our fitting approach using the Inskip et al. data as input, and found that the estimated physical parameters remain practically the same (within 10 per cent). This is one of the four objects in the redshift range $1 < z < 1.4$ for which Spitzer IRS spectra are available.

3C 305.1 – The UV-to-submm SED of this object could also be well represented with a two-component model, this being the sum of an evolved stellar component and the AGN torus component.

Table A2. Same as Table A1, but for 3C 210. References: (1) Chiaberge et al. (2015), (2) Haas et al. (2008), (3) Podigachoski et al. (2015a).

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Table A3. Same as Table A1, but for 3C 256. References: (1) Simpson et al. (1999), (2) Haas et al. (2008), (3) Podigachoski et al. (2015a).

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Table A4. Same as Table A1, but for 3C 257. References: (1) Chiaberge et al. (2015), (2) Haas et al. (2008), (3) Podigachoski et al. (2015a), (4) Archibald et al. (2001).

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Table A5. Same as Table A1, but for 3C 266. References: (1) Best et al. (1997), (2) Haas et al. (2008), (3) Podigachoski et al. (2015a). The flux densities measured from the Spitzer IRS spectrum in the artificial broad-band filters centred at 27, 30, and 33 μm are 1.7 ± 0.3, 2.7 ± 0.4, and 3.2 ± 0.5 mJy, respectively.

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<td>70</td>
<td>7600 ± 2400</td>
<td>(3)</td>
</tr>
<tr>
<td>PACS160</td>
<td>160</td>
<td>29 400 ± 4100</td>
<td>(3)</td>
</tr>
<tr>
<td>SPIRE250</td>
<td>250</td>
<td>19 500 ± 5600</td>
<td>(3)</td>
</tr>
</tbody>
</table>

Table A6. Same as Table A1, but for 3C 297. References: (1) Chiaberge et al. (2015), (2) Haas et al. (2008), (3) Podigachoski et al. (2015a).

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (μm)</th>
<th>Flux density (μJy)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSTF606W</td>
<td>0.6</td>
<td>6.6 ± 0.2</td>
<td>(1)</td>
</tr>
<tr>
<td>HSTF140W</td>
<td>1.4</td>
<td>64.3 ± 0.2</td>
<td>(1)</td>
</tr>
<tr>
<td>IRAC1</td>
<td>3.6</td>
<td>119 ± 18</td>
<td>(2)</td>
</tr>
<tr>
<td>IRAC2</td>
<td>4.5</td>
<td>126 ± 19</td>
<td>(2)</td>
</tr>
<tr>
<td>IRAC3</td>
<td>5.8</td>
<td>122 ± 18</td>
<td>(2)</td>
</tr>
<tr>
<td>IRAC4</td>
<td>8.0</td>
<td>121 ± 18</td>
<td>(2)</td>
</tr>
<tr>
<td>MIPS1</td>
<td>24</td>
<td>432 ± 65</td>
<td>(2)</td>
</tr>
<tr>
<td>PACS70</td>
<td>70</td>
<td>12 600 ± 1200</td>
<td>(3)</td>
</tr>
<tr>
<td>PACS160</td>
<td>160</td>
<td>15 400 ± 2400</td>
<td>(3)</td>
</tr>
<tr>
<td>SPIRE250</td>
<td>250</td>
<td>24 500 ± 4300</td>
<td>(3)</td>
</tr>
</tbody>
</table>

Table A7. Same as Table A1, but for 3C 305.1. References: (1) Chiaberge et al. (2015), (2) Haas et al. (2008), (3) Podigachoski et al. (2015a).

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (μm)</th>
<th>Flux density (μJy)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSTF606W</td>
<td>0.6</td>
<td>10.7 ± 0.2</td>
<td>(1)</td>
</tr>
<tr>
<td>HSTF140W</td>
<td>1.4</td>
<td>60.3 ± 0.2</td>
<td>(1)</td>
</tr>
<tr>
<td>IRAC1</td>
<td>3.6</td>
<td>181 ± 27</td>
<td>(2)</td>
</tr>
<tr>
<td>IRAC2</td>
<td>4.5</td>
<td>282 ± 42</td>
<td>(2)</td>
</tr>
<tr>
<td>IRAC3</td>
<td>5.8</td>
<td>495 ± 74</td>
<td>(2)</td>
</tr>
<tr>
<td>IRAC4</td>
<td>8.0</td>
<td>972 ± 146</td>
<td>(2)</td>
</tr>
<tr>
<td>IRS</td>
<td>16</td>
<td>2410 ± 362</td>
<td>(2)</td>
</tr>
<tr>
<td>MIPS1</td>
<td>24</td>
<td>2490 ± 374</td>
<td>(2)</td>
</tr>
<tr>
<td>PACS70</td>
<td>70</td>
<td>24 000 ± 2300</td>
<td>(3)</td>
</tr>
<tr>
<td>PACS160</td>
<td>160</td>
<td>40 400 ± 4300</td>
<td>(3)</td>
</tr>
<tr>
<td>SPIRE250</td>
<td>250</td>
<td>34 900 ± 6000</td>
<td>(3)</td>
</tr>
</tbody>
</table>

In this case, the results for the evolved component would remain unchanged, whereas the luminosity of the torus would increase.

3C 324 – This is one of the four objects in the redshift range 1 < z < 1.4 for which Spitzer IRS spectra are available.

3C 356 – 3C 356 has only two strong Herschel detections, however, its redshift of z = 1.08 ensures that the PACS 160 μm band probes emission beyond 70 μm, hence it is included in our sample.

This is one of the four objects in the redshift range 1 < z < 1.4 for which Spitzer IRS spectra are available.

3C 368 – The optical/UV spectral shape requiring a relatively low age of the evolved stellar population, together with the shape of the NIR SED traced by the shorter Spitzer bands suggest that some AGN contribution is likely present in the optical photometry of this object. This might be consistent with Best et al. (1998a), who argued that 3C 368 has the strongest alignment effect among the ones studied in their sample, so that the non-stellar contribution to the K-band photometry is about 30 per cent. This is one of the four objects in the redshift range 1 < z < 1.4 for which Spitzer IRS spectra are available.

3C 454.1 – The UV-to-submm SED of this object might also be well represented with a two-component model, this being the sum
Table A10. Same as Table A1, but for 3C 368. References: (1) Best et al. (1997), (2) Haas et al. (2008), (3) Podigachoski et al. (2015a), (4) Archibald et al. (2001). The flux densities measured from the Spitzer IRS spectrum in the artificial broad-band filters centred at 27, 30, and 33 µm are 6.4 ± 1.0, 7.6 ± 1.1 and 12.2 ± 1.8 mJy, respectively.

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (µm)</th>
<th>Flux density (µJy)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSTF702W</td>
<td>0.7</td>
<td>21.7 ± 2.6</td>
<td>(1)</td>
</tr>
<tr>
<td>HSTF791W</td>
<td>0.8</td>
<td>27.5 ± 4.1</td>
<td>(1)</td>
</tr>
<tr>
<td>UKIRTJ</td>
<td>1.2</td>
<td>66.1 ± 9.1</td>
<td>(1)</td>
</tr>
<tr>
<td>UKIRTK</td>
<td>2.2</td>
<td>99.3 ± 13.7</td>
<td>(1)</td>
</tr>
<tr>
<td>IRAC1</td>
<td>3.6</td>
<td>126 ± 19</td>
<td>(2)</td>
</tr>
<tr>
<td>IRAC2</td>
<td>4.5</td>
<td>112 ± 17</td>
<td>(2)</td>
</tr>
<tr>
<td>IRAC3</td>
<td>5.8</td>
<td>112 ± 17</td>
<td>(2)</td>
</tr>
<tr>
<td>IRAC4</td>
<td>8.0</td>
<td>210 ± 32</td>
<td>(2)</td>
</tr>
<tr>
<td>IRS</td>
<td>16</td>
<td>1370 ± 206</td>
<td>(2)</td>
</tr>
<tr>
<td>MIPS1</td>
<td>24</td>
<td>3250 ± 488</td>
<td>(2)</td>
</tr>
<tr>
<td>PACS70</td>
<td>70</td>
<td>29 900 ± 2000</td>
<td>(3)</td>
</tr>
<tr>
<td>PACS160</td>
<td>160</td>
<td>61 500 ± 4800</td>
<td>(3)</td>
</tr>
<tr>
<td>SPIRE250</td>
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<td>44 400 ± 7400</td>
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</tr>
<tr>
<td>SPIRE350</td>
<td>350</td>
<td>23 800 ± 6200</td>
<td>(3)</td>
</tr>
<tr>
<td>SCUBA850</td>
<td>850</td>
<td>4080 ± 1080</td>
<td>(4)</td>
</tr>
</tbody>
</table>

Table A11. Same as Table A1, but for 3C 454.1. References: (1) Chiaberge et al. (2015), (2) Haas et al. (2008), (3) Podigachoski et al. (2015a).

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (µm)</th>
<th>Flux density (µJy)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HST3F606W</td>
<td>0.6</td>
<td>3.6 ± 0.4</td>
<td>(1)</td>
</tr>
<tr>
<td>HST3F140W</td>
<td>1.4</td>
<td>53.5 ± 0.2</td>
<td>(1)</td>
</tr>
<tr>
<td>IRAC1</td>
<td>3.6</td>
<td>77 ± 12</td>
<td>(2)</td>
</tr>
<tr>
<td>IRAC2</td>
<td>4.5</td>
<td>76 ± 11</td>
<td>(2)</td>
</tr>
<tr>
<td>IRAC3</td>
<td>5.8</td>
<td>112 ± 17</td>
<td>(2)</td>
</tr>
<tr>
<td>IRAC4</td>
<td>8.0</td>
<td>135 ± 20</td>
<td>(2)</td>
</tr>
<tr>
<td>IRS</td>
<td>16</td>
<td>612 ± 92</td>
<td>(2)</td>
</tr>
<tr>
<td>MIPS1</td>
<td>24</td>
<td>1500 ± 225</td>
<td>(2)</td>
</tr>
<tr>
<td>PACS70</td>
<td>70</td>
<td>13 700 ± 2500</td>
<td>(3)</td>
</tr>
<tr>
<td>PACS160</td>
<td>160</td>
<td>37 000 ± 4700</td>
<td>(3)</td>
</tr>
<tr>
<td>SPIRE250</td>
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</tr>
<tr>
<td>SPIRE350</td>
<td>350</td>
<td>26 700 ± 10 400</td>
<td>(3)</td>
</tr>
</tbody>
</table>

Table A12. Same as Table A1, but for 3C 470. References: (1) Best et al. (1997), (2) Haas et al. (2008), (3) Podigachoski et al. (2015a), (4) Archibald et al. (2001).

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (µm)</th>
<th>Flux density (µJy)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
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<td>HSTF785LP</td>
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<td>3.9 ± 1.4</td>
<td>(1)</td>
</tr>
<tr>
<td>UKIRTK</td>
<td>2.2</td>
<td>39.9 ± 5.5</td>
<td>(1)</td>
</tr>
<tr>
<td>IRAC1</td>
<td>3.6</td>
<td>50 ± 7</td>
<td>(2)</td>
</tr>
<tr>
<td>IRAC2</td>
<td>4.5</td>
<td>75 ± 11</td>
<td>(2)</td>
</tr>
<tr>
<td>IRAC3</td>
<td>5.8</td>
<td>72 ± 11</td>
<td>(2)</td>
</tr>
<tr>
<td>IRAC4</td>
<td>8.0</td>
<td>266 ± 40</td>
<td>(2)</td>
</tr>
<tr>
<td>IRS</td>
<td>16</td>
<td>1510 ± 227</td>
<td>(2)</td>
</tr>
<tr>
<td>MIPS1</td>
<td>24</td>
<td>2650 ± 398</td>
<td>(2)</td>
</tr>
<tr>
<td>PACS70</td>
<td>70</td>
<td>16 000 ± 2700</td>
<td>(3)</td>
</tr>
<tr>
<td>PACS160</td>
<td>160</td>
<td>29 300 ± 5100</td>
<td>(3)</td>
</tr>
<tr>
<td>SPIRE250</td>
<td>250</td>
<td>48 000 ± 6500</td>
<td>(3)</td>
</tr>
<tr>
<td>SPIRE350</td>
<td>350</td>
<td>36 300 ± 5200</td>
<td>(3)</td>
</tr>
<tr>
<td>SCUBA850</td>
<td>850</td>
<td>5640 ± 1080</td>
<td>(4)</td>
</tr>
</tbody>
</table>

of an evolved stellar component and the AGN torus component. In this case, the results for the evolved component would remain unchanged, whereas the luminosity of the torus would increase.

3C 470 – It is the only object in our sample, in which the stellar mass of the young stellar component is significantly larger than that of the evolved stellar component.