PROPERTIES AND EXPECTED NUMBER COUNTS OF ACTIVE GALAXIC NUCLEI AND THEIR HOSTS IN THE FAR-INFRARED

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ABSTRACT

Telescopes like Herschel and the Atacama Large Millimeter/submillimeter Array (ALMA) are creating new opportunities to study sources in the far-infrared (FIR), a wavelength region dominated by cold dust emission. Probing cold dust in active galaxies allows for study of the star formation history of active galactic nucleus (AGN) hosts. The FIR is also an important spectral region for observing AGNs which are heavily enshrouded by dust, such as Compton thick (CT) AGNs. By using information from deep X-ray surveys and cosmic X-ray background synthesis models, we compute Cloudy photoionization simulations which are used to predict the spectral energy distribution (SED) of AGNs in the FIR. Expected differential number counts of AGNs and their host galaxies are calculated in the Herschel bands. The expected contribution of AGNs and their hosts to the cosmic infrared background (CIRB) and the infrared luminosity density are also computed. Multiple star formation scenarios are investigated using a modified blackbody star formation SED. It is found that FIR observations at ~500 μm are an excellent tool in determining the star formation history of AGN hosts. Additionally, the AGN contribution to the CIRB can be used to determine whether star formation in AGN hosts evolves differently than in normal galaxies. The contribution of CT AGNs to the bright end differential number counts and to the bright source infrared luminosity density is a good test of AGN evolution models where quasars are triggered by major mergers.

Key words: galaxies: active – galaxies: evolution – infrared: galaxies – quasars: general – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

Thanks to the Spitzer Space Telescope and its imaging and spectroscopic instrument suite (Werner et al. 2004), it has recently been found that active galactic nuclei (AGNs) can dominate the near- and mid-infrared luminosity and make a significant contribution to the 8–1000 μm luminosity, $L_{IR}$, of AGN host galaxies (Houck et al. 2005; Yan et al. 2005; Weedman et al. 2006; Soifer et al. 2008, and references therein). Specifically, a large fraction of ultraluminous infrared galaxies ($L_{IR} > 10^{12} L_{⊙}$; ULIRGs) and luminous infrared galaxies ($L_{IR} > 10^{11} L_{⊙}$; LIRGs) appear to host luminous AGNs (e.g., Dey et al. 2008; Donley et al. 2008; Fiore et al. 2008, 2009; Yuan et al. 2010). In the far-infrared (FIR) it is more difficult to determine the AGN contribution to the combined AGN and host observed flux as little is known about the AGN spectral energy distribution (SED) at these wavelengths. For the purposes of this study, we define the FIR as 70–1000 μm.

The next several years will see a huge growth in high quality FIR and submillimeter spectral data due to telescopes like the Herschel Space Observatory and the Atacama Large Millimeter/submillimeter Array (ALMA). Herschel, launched in 2009 May, offers unprecedented coverage of the FIR and submillimeter spectral regions (Pilbratt et al. 2010). Herschel carries two imaging photometers, the Photodetector Array Camera and Spectrometer (PACS), which has photometric bands at 70, 100, and 160 μm (Poglitsch et al. 2010), and the Spectral and Photometric Imaging Receiver (SPIRE), which has photometric bands at 250, 350, and 500 μm (Griffin et al. 2010). As one of the primary science goals of Herschel is to study the evolution of galaxies (Pilbratt et al. 2010), three wide area surveys of various depths are being undertaken. The PACS evolutionary probe (PEP) will cover ~3 deg$^2$ and will observe some fields, such as the GOODS fields, down to the depth of the 100 and 160 μm confusion limits of a few mJy (Berta et al. 2010). The Herschel Multi-tiered Extragalactic Survey (HerMES) will observe ~70 deg$^2$ with SPIRE, reaching 5σ depths of a couple mJy at 250 μm in some fields (Oliver et al. 2010; Roseboom et al. 2010). Observing ~510 deg$^2$ with both PACS and SPIRE, the Herschel Atlas (H-ATLAS) survey is the largest open time survey being undertaken by Herschel (Eales et al. 2010). H-ATLAS will reach 5σ depths of 67 mJy at 100 μm and 53 mJy at 500 μm (Eales et al. 2010; Ibar et al. 2010; Pascale et al. 2010). The ground-based instrument Submillimeter Common-User Bolometer Array 2 (SCUBA-2) will operate at 450 and 850 μm and will offer an intermediate sensitivity and mapping speed between those of Herschel and ALMA (Holland et al. 2006). Also ground-based ALMA is an imaging and spectroscopic instrument operating in the millimeter and submillimeter regime. The ALMA primer notes that at full science operations, starting in late 2012, ALMA will have a 450 μm band (Band 9) with a continuum sensitivity of 0.69 mJy and a 350 μm band (Band 10) with a sensitivity of 1.1 mJy, along with bands at longer wavelengths. The 450 μm band will be available for early science operations in mid 2011, albeit at reduced sensitivity. Herschel’s observing capabilities, and in particular the SPIRE deep and wide surveys at 250, 350, and 500 μm, will provide promising candidate targets for ALMA early science operations.

It is expected that AGNs and their hosts will be readily detected in the FIR by Herschel. Hatziminaoglou et al. (2010) found that a third of their AGN sample had Herschel 5σ detections at 250 μm with $f_{250, μm} > 12.8$ mJy, where $f_{250, μm}$ is the 250 μm flux. The FIR flux from AGNs and their hosts will be due to dust heated by a combination of AGN radiation and star formation. Observations suggest that only 3%–9% of...
submillimeter galaxies are dominated by AGN emission in the submillimeter (Laird et al. 2010). However, a large portion of galaxies, nearly 50% of the galaxies in the infrared-selected sample of Yuan et al. (2010), show strong infrared emission from both star formation and AGN activity. Consequently, the AGN contribution to the FIR emission of AGN hosts must be considered in order to not overestimate star formation rates (SFRs) in AGN hosts.

As the FIR SED of AGNs is expected to generally be dominated by star formation (e.g., Hatziminaoglou et al. 2010; Lutz et al. 2010), FIR observations will inform investigations of the star formation history of AGN hosts. By comparing the star formation history of AGN hosts and normal galaxies, the role of AGNs in galaxy evolution will be constrained. Understanding AGN host star formation history is therefore an important tool in determining what processes trigger AGNs. For example, Sanders et al. (1988) proposed that galaxy mergers trigger both intense starbursts and quasar activity. Recent observations and simulations support this model (Page et al. 2004; Hopkins et al. 2006; Rigopoulou et al. 2009; Draper & Ballantyne 2010; Kelly et al. 2010). Page et al. (2004) found that type 2 AGNs tend to have higher SFRs than type 1 AGNs. Draper & Ballantyne (2010) found that a significant fraction of Compton thick (CT) AGNs, AGNs with an X-ray obscuring column density $N_{\text{H}} > 10^{24}$ cm$^{-2}$, are quasars which are accreting very rapidly, as predicted by simulations by Hopkins et al. (2006) and others. However, it appears that this model may only be applicable for the most powerful AGNs and that Seyfert strength AGNs may evolve more secularly (Ballantyne et al. 2006a; Hasinger 2008; Lutz et al. 2010; Narayanan et al. 2010). In order to determine the applicability of the merger-driven evolution and secular evolution models, the star formation history of AGN hosts must be accurately determined. This requires a robust method of identifying AGN hosts and the AGN contribution to the FIR emission.

FIR emission from AGNs comes from the “torus” of dusty gas, which, according to the unified scheme, surrounds the central engine of all AGNs (e.g., Antonucci 1993). This dusty torus will absorb energy from the central engine of the AGN and re-radiate this energy in the infrared. The temperature of the dust, and therefore the peak wavelength of the infrared radiation, is dependent on the density of the obscuring gas and the distance of the obscuring gas from the central engine (e.g., Ballantyne et al. 2006b), among other parameters like the geometry of the obscuring torus (e.g., Hatziminaoglou et al. 2009). It appears that the infrared SED of most X-ray-selected AGNs peaks in the mid-infrared (e.g., Elvis et al. 1994; Netzer et al. 2007). However, due to the large amount of dust required to reach CT levels of obscuration, it is expected that the clouds of dusty gas in CT AGNs will have a greater spatial extent than in less obscured AGNs. Therefore, CT AGNs will have a significant reservoir of dusty gas which is cooler than most AGN-related dust clouds. This cooler dust component will cause CT AGNs to be brighter in the FIR than unobscured AGNs.

Indeed, studies suggest that bright galaxies detected in the FIR host a large number of heavily obscured, $N_{\text{H}} > 10^{23}$ cm$^{-2}$, and possibly CT AGNs (e.g., Alexander et al. 2005a, 2005b; Bongiovanni et al. 2010; Wilman et al. 2010). Mullaney et al. (2010) found that 45%–75% of the 1 Ms CDF-S X-ray sources will be detected by Herschel at 100 μm and that deep infrared observations with Herschel will allow for a significant fraction of the CT AGN population to be identified. Also, since X-ray selection misses nearly half of all infrared-identified AGNs (Fu et al. 2010) it is expected that FIR telescopes like Herschel and ALMA will detect highly obscured AGNs that are missed by the deep X-ray surveys. However, there is an open debate as to how many of these infrared AGNs reach CT levels of obscuration. Fiore et al. (2009) find that up to 90% of sources with $f_{\text{X}} > 500$ μJy and $f_{\text{X}}/f_{R} > 1000$ are CT AGNs, where $f_{\text{X}}$ is the 24 μm flux and $f_{R}$ is the R-band flux. Conversely, Georgantopolous et al. (2011) find a more moderate fraction of CT AGNs for this population. When looking at similar infrared excess sources, Georgakakis et al. (2010) found no strong evidence suggesting that these sources host AGNs with CT levels of obscuration. Therefore, further study of the infrared properties of AGNs is important in determining exactly how many CT AGNs are hidden within dusty LIRGs.

This work makes predictions for FIR AGN number counts, contribution to the CIRB, and luminosity density using a population synthesis model informed by constraints from the cosmic X-ray background (CXB) and deep X-ray surveys, including the Eddington ratio dependent CT fraction, $f_{\text{CT}}$, of the composite model investigated by Draper & Ballantyne (2010). The effect of various AGN host star formation scenarios are also investigated. The calculation of the model SEDs is discussed in Section 2. Predictions for bare AGNs are presented in Section 3 followed by predictions for various host star formation scenarios in Section 4. In Sections 5 and 6 the results are discussed and summarized. A ΛCDM cosmology is assumed as necessary, with $h_{0} = 0.7$, $\Omega_{m} = 0.3$, and $\Omega_{\Lambda} = 0.7$ (Hinshaw et al. 2009).

2. CALCULATION OF AGN SEDs

As the goal of this study is to make predictions of the average FIR properties of AGNs, SEDs are used which are representative of an ensemble of AGNs at a given 2–10 keV luminosity, $L_{X}$, and $z$, instead of using an SED template based on observations of a statistically small set of AGNs. Since AGN IR emission is primarily due to the obscuring gas and dust re-radiating absorbed X-ray emission, photoionization simulations allow for the computation of the IR emission of an average AGN with a given $L_{X}$ and $N_{\text{H}}$. Also, this SED computation method provides an opportunity to explore the parameter space of obscuring gas location, density distribution, and dust content, which, upon comparison with observations, may offer constraints for these physical parameters.

Similarly to Ballantyne et al. (2006b), the IR AGN SEDs are calculated using the photoionization code Cloudy version C08.00 (Ferland et al. 1998). Cloudy includes the complicated physics of radiative transfer through dusty gas and uses a physical dust model which takes into account silicate and graphite grains along with polycyclic hydrocarbons. This technique does necessitate a simplification of the IR emitting region, which might actually be quite complex (e.g., Hatziminaoglou et al. 2009; Höning et al. 2010). However, since our purpose is to describe average properties of AGNs, and not to model individual objects, this technique is an appropriate method of SED calculation. This assumption will be tested by comparing the model SEDs against real data in Section 2.3.

2.1. Cloudy Model Setup

Each Cloudy model is set up such that a constant AGN spectrum, characterized by $L_{X}$, is incident upon a cloud with inner radius $r$ from the continuum source. The inner radius $r$ is set to 10 pc. Compton thin clouds are assigned a uniform
hydrogen density $n_H = 10^4 \, \text{cm}^{-3}$, as is typical of molecular clouds. In order to prevent the dust mass from becoming too large, the CT clouds are assigned $n_H = 10^6 \, \text{cm}^{-3}$. Molecular clouds of this density are not uncommon and have been observed in the Large Magellanic Cloud (Rubio et al. 2009) and in the Orion Nebula (Persson et al. 2007). Simulations were also run with $r = 1 \, \text{pc}$ and $n_H = 10^4 \, \text{cm}^{-3}$ for both Compton thin and CT clouds to test the sensitivity of the results to these assumptions, which is discussed later.

The Cloudy model input files are similar to those used by Ballantyne et al. (2006b), with the following improvements. Instead of using a constant $\alpha_{OX}$ for all AGNs, the Steffen et al. (2006) $\alpha_{OX} - L_{23\text{keV}}$ relation is used here to determine $\alpha_{OX}$. The most significant improvement made includes dividing the AGN population into Eddington ratio bins, high ($L/L_{\text{Edd}} > 0.9$, where $L$ is the bolometric luminosity found using the bolometric correction by Marconi et al. 2004 and $L_{\text{Edd}}$ is the Eddington luminosity), moderate ($0.9 < L/L_{\text{Edd}} < 0.01$), and low ($0.1 < L/L_{\text{Edd}}$), as described by Draper & Ballantyne (2010). Both the composite and original models of Draper & Ballantyne (2010) are investigated.

The $f_{\text{CT}}$ of the composite model is Eddington ratio dependent and finds that $\sim 86\%$ of AGNs accreting at greater than $90\%$ of their Eddington rate are CT AGNs. The covering factor is set as the CT fraction, $f_{\text{CT}}$. The original model assumes that CT AGNs are a simple extension of the Compton thin type 2 population and that $\sim 44\%$ of type 2 AGNs are CT. Since the covering factor is set assuming the unified scheme holds, the covering factors are Eddington ratio dependent since $f_{\text{CT}}$ is Eddington ratio dependent. For CT objects the covering factor is set as the CT fraction, $f_{\text{CT}}$. For objects with $22 \leq \log N_H < 24$ the covering factor is set as $(1.0 - f_{\text{CT}}) f_2$, where $f_2$ is the type 2 fraction and is calculated as discussed in Section 2.2 of Draper & Ballantyne (2009). The covering factor for objects with $20 \leq \log N_H < 22$ is set to $(1.0 - f_{\text{CT}})(1.0 - f_2)$. As the covering factor is dependent on the Eddington ratio and varies from $z = 0$ to 1, Cloudy models had to be calculated as a function of $z$ and $L/L_{\text{Edd}}$ for each $L_X$ and $N_H$.

There is evidence that different levels of obscuration in quasars might be related by an evolutionary scenario instead of by orientation effects (e.g., Sanders et al. 1988; Page et al. 2004; Draper & Ballantyne 2010; Donley et al. 2010), and thus the covering fraction need not be related to $f_{\text{CT}}$ or $f_2$. Ballantyne et al. (2006b) found that the unified model assumption holds for lower luminosity quasars and Seyfert galaxies but does not seem to hold for high-luminosity quasars, possibly due to a different evolution for high luminosity, and therefore high Eddington ratio, quasars. Here, this issue is addressed by using the Eddington ratio dependent $f_{\text{CT}}$ of the composite model, which takes into account the different evolution of high Eddington ratio quasars from the moderate and low Eddington ratio AGNs.

2.2. The Model Grids

As this investigation of the FIR properties of AGNs is informed by the constraints offered by the CXRB and X-ray observations of AGNs, SEDs are calculated as a function of $\log L_X$ and $z$. It is assumed that the redshift evolution of $f_2$ halts at $z = 1$, thus models are computed up to $z = 1$ and the $z = 1$ models are used at $z > 1$. Therefore, we compute Cloudy models for $z = 0$–1, in steps of 0.05, and $\log L_X = 41.5$–48, in steps of 0.25. For each luminosity and redshift, Cloudy models are calculated for each $\log N_H = 20.0, 20.5,$

For each Eddington ratio bin, the weighted average of the reflection components of each $N_H$ is added to the net transmitted continua of each $N_H$ to create the “unified SEDs.” The final SEDs are calculated in three categories: type 1, type 2 but Compton thin (which will be referred to as “type 2”), and CT, for each Eddington ratio bin. The type 1 SED is an average of the 24–25 $L_X$ model SEDs at a given $z$ and two SEDs are interpolated between consecutive $z$ model SEDs at a given $L_X$. A convergence test was conducted using twice as many steps in both $L_X$ and $z$; it was found that the step size used here is adequate for convergence.

To create final SEDs from the 18711 Cloudy models, we follow the method described by Ballantyne et al. (2006b). For each Eddington ratio bin, the weighted average of the reflection components of each $N_H$ is added to the net transmitted continua of each $N_H$ to create the “unified SEDs.” The final SEDs are calculated in three categories: type 1, type 2 but Compton thin (which will be referred to as “type 2”), and CT, for each Eddington ratio bin. The type 1 SED is an average of the 22 $L_X$ model SEDs, the type 2 SED is an average of the 24 $L_X$ model SEDs, and the CT SED is an average of the 24 $L_X$ model SEDs. At this point, for each $(L_X, z)$ pair there is a type 1, type 2, and CT SED for each Eddington ratio bin. Figure 1 shows the rest-frame $L_X$ for $z = 43$ and $z = 0.45$ ($f_{\text{CT}} = 0.86$ and $f_2 = 0.78$). The type 1 SED is shown in red, the type 2 SED is shown in green, while the Compton thick SED is shown in blue.

(A color version of this figure is available in the online journal.)

Figure 1. Rest-frame SEDs for high Eddington ratio AGNs ($L/L_{\text{Edd}} > 0.9$) with $\log L_X = 43$ and $z = 0.45$ ($f_{\text{CT}} = 0.86$ and $f_2 = 0.78$). The type 1 SED is shown in red, the type 2 SED is shown in green, while the Compton thick SED is shown in blue.

. . . , 24.5, 25.0 cm$^{-2}$. Since the covering factor is Eddington ratio dependent, Cloudy models had to be calculated for each luminosity, redshift, and column density for each of the three Eddington ratio bins. This resulted in 18,711 individual Cloudy models for each $r$ investigated and an additional 5103 Cloudy models to investigate the sensitivity of results to the hydrogen density, $n_H$, of the CT clouds.

As we need to run 33 models for each $(L_X, z)$ pair, it is computationally prohibitive to run models on a finer grid. Therefore, we have linearly interpolated between the SEDs to allow for a finer grid in the calculations. Thus, eight SEDs are interpolated between consecutive $\log L_X$ model SEDs at a given $z$ and two SEDs are interpolated between consecutive $z$ model SEDs at a given $L_X$. A convergence test was conducted using twice as many steps in both $L_X$ and $z$; it was found that the step size used here is adequate for convergence.

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2.3. Properties of AGN Model SEDs

The model SEDs were tested in the same manner as by Ballantyne et al. (2006b) to assure the assumptions used to compute that the SEDs were appropriate and that the model
SEDs are consistent with observed SED trends. As little is known about AGN FIR SEDs, these tests primarily investigate the mid-infrared properties of the model SEDs. The mid-infrared to X-ray flux colors were examined and found to be consistent with the mid-infrared properties of the model SEDs. The mid-infrared fluxes agree reasonably well with the correlation, especially the composite model SEDs best describe the average AGN SEDs.

The model SEDs were also tested against the more re-

S. The fact that the SEDs fit this relation better than the Compton thick SEDs. The model SEDs are found to be consistent with the observed AGN SED trends.

The model SEDs also tested against the more recently discovered correlation between mid-infrared luminosity, $L_{12.3 \mu m}$, and $L_X$ for a sample of local Seyferts (Gandhi et al. 2009). Figure 2 compares the $z = 0.05$ model SEDs to the local best-fit correlation found by Gandhi et al. (2009). The model SEDs agree reasonably well with the correlation, especially the type 1 SEDs. At high luminosities the CT SEDs appear to have a slight X-ray excess compared to the local Seyfert correlation. This is due to the CT SEDs including more power radiated in the FIR, and consequently less power radiated in the mid-infrared, than the Compton thin SEDs. The $r = 1.0$ pc model SEDs do match the $L_{12.3 \mu m} - L_X$ relation better than the $r = 10$ pc model SEDs; however, the $r = 10$ pc model SEDs best describe the general mid-infrared properties of an ensemble of AGNs (see Ballantyne et al. 2006b). The fact that the $r = 1.0$ pc model SEDs fit this relation better than the $r = 10$ pc model SEDs shows that the distribution of gas and dust in the AGN dusty torus is an important effect in the mid-infrared. In order for the models used here to better approximate the Gandhi et al. (2009) relation, the geometry of the dusty torus should be carefully

taken into account. The FIR SEDs are dominated by star formation, so the geometric details of the hot dust close to the central engine should not affect the results of this study. Also, this study is focused on the integral properties of a large number of AGNs, detailed modeling of the torus geometry is beyond the scope of this current study and we leave this for future work. Overall, the model SEDs are an appropriate representation of average AGN SEDs.

### 3. Predictions for Bare AGNs

In this section, we present predictions for differential number counts, the AGN contribution to the cosmic infrared background (CIRB), and luminosity density, based on the model SEDs. The population synthesis model last described by Draper & Ballantyne (2010) is used to incorporate the information about and the constraints on the AGN population from deep hard X-ray surveys and the CXRB into infrared predictions.

#### 3.1. Differential Number Counts

The number of sources per square degree with flux greater than $S$, $N(>S)$ is found by

$$N(>S) = \frac{K_{deg}^{*}}{H_0} \times \int_{z_{min}}^{z_{max}} \int_{\log L_X}^{\log L_X^{max}} \frac{d\Phi_2(L_X, z)}{d \log L_X} \times \frac{d^2}{(1+z)^2[\Omega_0(1+z)^3 + \Omega_m^1/2]^{1/2}} d \log L_X dz, \hspace{1cm} (1)$$

where the factor $K_{deg}^{*} = 3.05 \times 10^{-4}$ converts from $sr^{-1}$ to $deg^{-2}$. $d\Phi_2(L_X, z)/d \log L_X$ is the evolving Eddington ratio space density computed by Draper & Ballantyne (2010), in $Mpc^{-3}$, $d)$ is the luminosity distance, and $log L_X$ is the 2–10 keV rest-frame luminosity corresponding to the observed-frame infrared flux S at redshift z. The differential number counts are found by taking the derivative of $N(>S)$ with respect to $S$, $dN(>S)/dS$. The differential number counts were also calculated directly. However, due to the coarseness of the $L_X$ and z grid used, the differential number counts contained numerical artifacts at brighter fluxes. The predictions from the two calculation methods are in agreement; however, computing the integral number counts on a very fine flux grid and then taking the derivative with respect to flux minimizes the numerical noise found in direct calculation of the differential number counts.

The Euclidean normalized differential number counts for 70, 100, 160, and 250 $\mu m$ are shown in Figure 3.3 Plots are not shown for the 350 and 500 $\mu m$ bands because, as evident in Figure 1, the flux due to the AGN is very small at such long wavelengths; for example, at 10 mJy the 500 $\mu m$ band $dN(>S)/dS \approx 0.4$ AGN hosts mJy$^{-1}$ deg$^{-2}$. The black lines show the predictions for the composite model and the cyan lines show the predictions for the original model. For ease in interpreting the figure, the low, moderate, and high Eddington ratio bins have been combined and the total differential counts are shown (see Section 5.4 for a discussion about the contribution from the various Eddington ratio bins). As expected, the differential

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3 Fluxes are calculated at the filter nominal wavelengths. Using the full filter transmission function to calculate the $dN/dS$ provides a result which is within a factor of 1.05 of that obtained when calculating the flux at the filter nominal wavelength. Thus, the error due to calculating the fluxes at the filter nominal wavelength instead of using the full filter profile is negligible compared to the uncertainties in the model and the measurements.
number counts for bare AGNs are very small at long wavelengths because the AGNs tend to create hot dust. Therefore, long wavelengths can be used to investigate the star formation in AGN hosts. For both the original and composite models, CT AGNs dominate the bright end of the differential counts, especially at wavelengths longer than 70 μm. In both models the type 2 AGNs dominate at lower fluxes and the type 1 AGNs contribute significantly less than their obscured counterparts at all wavelengths. The original model and composite model differential counts peak at about the same flux for each wavelength and have similar bright end slopes. However, the original model peaks above the composite model and declines faster on the lower flux level end.

It is important to consider the dependence of these predictions on the parameters of the distance of the inner edge of the cloud from the ionizing source, $r$, and the $n_H$ of the CT clouds, $n_{H, CT}$. As seen in Figure 4, when $r = 1$ pc the differential counts are greatly reduced at all FIR wavelengths because the dust is hot and radiating more energy in the mid-infrared. Contrastingly, when $r > 10$ pc the differential counts are enhanced due to the dust being farther from the illuminating source and therefore cooler. Similarly, when $n_{H, CT} = 10^4$ cm$^{-3}$ the differential counts are slightly enhanced in the FIR due to the greater spatial extent of the cloud. However, since the combined AGN and host SED will be dominated by star formation at longer wavelengths, and there is likely to be variation among individual objects, the exact values for $r$ and $n_{H, CT}$ used will have little effect on the final predictions.

### 3.2. CIRB

The AGN contribution to the CIRB is calculated similarly to population synthesis models looking at the CXRB, but exchanging the X-ray spectrum with the infrared spectrum.

$$I_\nu(v) = \frac{c}{H_0} \int_{z_{\text{min}}}^{z_{\text{max}}} \int_{\log L_X^{\text{min}}}^{\log L_X^{\text{max}}} \frac{d\Phi_\lambda(L_X, z)}{d \log L_X} S_\nu(L_X, z) dL_X d \log L_X d\Omega_1 \Omega_2 \Omega_3 \Omega_4$$

where $S_\nu(L_X, z)$ is the observed-frame AGN model SED, in Jy sr$^{-1}$, computed with $L_X$ at redshift $z$. As there is little knowledge about the SEDs of AGNs in the FIR, there are very few constraints on the AGN contribution to the CIRB. Jauzac et al. (2011) claim that AGNs contribute $\lesssim$10% of the CIRB at $z < 1.5$, based on Spitzer observations in the GOODS and COSMOS fields. By extrapolating from CXRB models to the CIRB using rough AGN SED templates, Silva et al. (2004) predict that bare AGNs contribute $\sim 0.3\%$ of the CIRB at 160 μm. Using a method similar to the one described here, Ballantyne & Papovich (2007) predict that bare AGNs contribute $\sim 0.9\%$ of the CIRB at 160 μm. Here, it is found that both the composite and original models predict that bare AGNs contribute $\sim 0.9\%$ of the CIRB at 160 μm. As seen in Figure 5, type 2 AGNs dominate the CIRB at lower wavelengths and at higher wavelengths CT AGNs dominate the AGN contribution to the CIRB. At wavelengths greater than $\sim 100$ μm the original model and the composite model predict very similar contributions of AGNs to the CIRB. Below $\sim 100$ μm the composite model predicts a higher contribution to the CIRB by AGNs than the original model.

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4 Here, we assume that the intensity of the CIRB at 160 μm is 12.84 nW m$^{-2}$ sr$^{-1}$ (Altieri et al. 2010).
3.3. Luminosity Density

The cosmic infrared luminosity density and its evolution are good indicators of the SFR density and the evolution of star formation in the universe. However, infrared luminosity density is significantly contaminated by AGNs, thus making it important to understand the contribution of AGNs to the infrared luminosity density and how the AGN contribution to the infrared luminosity density evolves. The 8–1000 μm AGN luminosity density, $\rho_{\text{IR}}$, is calculated as

$$\rho_{\text{IR}}(z) = \int_{L_{\text{IR,max}}}^{L_{\text{IR, min}}} \frac{d\Phi^*_{\lambda}(L_{\text{IR}}, z)}{d \log L_{\text{IR}}} d \log L_{\text{IR}},$$

where $d\Phi^*_{\lambda}/d \log L_{\text{IR}}$ is the evolving Eddington ratio space density calculated in Draper & Ballantyne (2010) in terms of the total infrared luminosity, i.e., a total infrared luminosity function for a population of AGNs with a specific Eddington ratio, which is found using the relation

$$\frac{d\Phi^*_{\lambda}(L_{\text{IR}}, z)}{d \log L_{\text{IR}}} = \frac{d\Phi^*_{\lambda}(L_{X}, z)}{d \log L_{X}} \frac{d \log L_{X}}{d \log L_{\text{IR}}},$$

As seen in Figure 6, both the composite and original models are in agreement with observations by Goto et al. (2010) at $z \approx 0.2$–0.8. For $z \gtrsim 1$ both models do not evolve fast enough to agree with the $\rho_{\text{IR}}$ and ULIRG AGN infrared luminosity density, $\rho_{\text{IR}}^{\text{ULIRG}}$. However, both models are in fairly good agreement with the high-redshift LIRG AGN luminosity density, $\rho_{\text{IR}}^{\text{LIRG}}$. Locally both the original and composite models underpredict the $\rho_{\text{IR}}^{\text{LIRG}}$ and overpredict the $\rho_{\text{IR}}^{\text{LIRG}}$, but are in agreement with the $\rho_{\text{IR}}^{\text{LIRG}}$, as measured by Goto et al. (2011). Due to the method used to separate the AGNs and star-forming galaxies in the samples of Goto et al. (2010, 2011), there is an uncertainty of up to 50% due to the complication of galaxies whose infrared SED is not clearly dominated by AGN activity nor by star formation (Goto et al. 2011). Also, by applying the same method of separating the contribution of AGNs and star-forming galaxies to the infrared luminosity density measured by Le Floc’h et al. (2005) using Spitzer 24 μm sources in the CDF-S, the local $\rho_{\text{IR}}^{\text{ULIRG}}$ is $\sim 0.4$ dex higher and in good agreement with local $\rho_{\text{IR}}^{\text{ULIRG}}$ predicted here.

4. ACCOUNTING FOR STAR FORMATION

The infrared SEDs of most AGNs are dominated by star formation (e.g., Franceschini et al. 2010). Unless the AGN host galaxy can be spatially resolved, it is very difficult to separate the AGN emission from the star formation emission. Therefore, it is important to consider how various AGN star formation scenarios will affect the predictions discussed above. In particular, a constant SFR is considered, keeping with the unified scheme. A star formation scenario consistent with the AGN evolution scenario discussed by Sanders et al. (1988) is also analyzed. Finally, star formation scenarios which include evolution of the SFR with redshift and AGN $L_{X}$ are considered.

To calculate the star formation SED for a given SFR, a modified blackbody spectrum characterized by the dust emissivity, $\beta$, and the dust temperate, $T_d$, is used. The Kennicutt (1998) relation,

$$\text{SFR} = 4.5 \times 10^{-44} L_{\text{IR}},$$

is used to determine $L_{\text{IR}}$, in erg s$^{-1}$, for a given SFR, in $M_\odot$ yr$^{-1}$, and the $L_{\text{IR}}$–$T_d$ relation from Amblard et al. (2010),

$$T_d = T_0 + \alpha \log (L_{\text{IR}}/L_\odot),$$
Figure 7. Euclidean normalized differential number counts for AGNs and host star formation at 70 μm for the various star formation scenarios using the composite model. Constant star formation is shown as black. The AGN evolution star formation scenario is shown as green. Star formation with the redshift evolution found by Serjeant et al. (2010) is shown as red. The line styles are the same as in Figure 3. The gray line shows the best-fit model galaxy differential number counts of Franceschini et al. (2010). (A color version of this figure is available in the online journal.)

is used to determine $T_0$. Using Herschel observations, Amblard et al. (2010) find $T_0 = 20.5$ K and $\alpha = 4.4$, using $\beta = 1.5$. Amblard et al. (2010) define $L_{IR}$ as the 8–1100 μm luminosity, instead of the 8–1000 μm luminosity as done here; however, for our purposes, the difference is negligible. The resulting star formation SEDs are in good agreement with the star formation templates presented by Rieke et al. (2009) at rest-frame wavelengths greater than 50 μm. The star formation SEDs are then added to the model SEDs discussed above to create the AGN+SF SED. The calculations discussed in Section 3 are repeated using the AGN+SF SEDs in place of the AGN model SEDs. Here, the predictions for the composite model are presented. A comparison of the predictions of the original and composite models is discussed in Section 5.2.

4.1. Constant Star Formation

The simplest star formation scenario is where AGN hosts have a constant SFR. Ballantyne & Papovich (2007) found that an average AGN SFR $= 1.0 M_\odot$ yr$^{-1}$ reproduces the AGN contribution to the mid-infrared portion of the CIRB as measured by Spitzer; thus for the constant star formation model we set SFR $= 1.0 M_\odot$ yr$^{-1}$. In keeping with the unified scheme, all AGNs have the same SFR regardless of spectroscopic type. The Euclidean normalized differential number counts for the constant star formation model are shown as the black lines in Figures 7–12. At wavelengths shorter than 350 μm, the number counts increase steeply from 0.01 mJy to $\sim$1 mJy and then remain approximately flat through $\sim$25 mJy. At wavelengths longer than 350 μm, the number counts turn over around 1 mJy and continue to decrease toward brighter flux levels. At all wavelengths the CT AGNs dominate the bright end counts above $\sim$1 mJy, with type 2 AGNs dominating at lower flux levels.

Figure 8. Euclidean normalized differential number counts for AGNs and host star formation at 100 μm for the various star formation scenarios using the composite model. Lines are the same as in Figure 7. Herschel data points are from Altieri et al. (2010) (stars) and Berta et al. (2010) (circles, GOODS-N; squares, Lockman XMM; and triangles, COSMOS). (A color version of this figure is available in the online journal.)

The black lines in Figure 13 show the AGN contribution to the CIRB for the constant star formation model. In this star formation scenario, AGNs contribute $\sim$4% of the CIRB at 160 μm. The AGN contribution to the CIRB is dominated by CT AGNs above 100 μm and type 2 AGNs also contribute significantly. The AGN contribution to the CIRB peaks at approximately the same wavelength as the CIRB itself peaks, $\sim$160 μm.
Figure 10. Euclidean normalized differential number counts for AGNs and host star formation at 250 μm for the various star formation scenarios using the composite model. Line colors and styles are the same as in Figure 7. Circles are data points from Herschel (Oliver et al. 2010) and asterisks show the multiply broken power-law model of Glenn et al. (2010).

(A color version of this figure is available in the online journal.)

Figure 11. Euclidean normalized differential number counts for AGNs and host star formation at 350 μm for the various star formation scenarios using the composite model. Line colors and styles are the same as in Figure 7. Additionally, the dotted gray line shows the expected continuum sensitivity of ALMA for an integration time of 60 s and a spectral resolution of 1 km s⁻¹. Circles are data points from Herschel (Oliver et al. 2010), the diamond is from SHARC II (Khan et al. 2007), and asterisks show the multiply broken power-law model of Glenn et al. (2010).

(A color version of this figure is available in the online journal.)

Figure 12. Euclidean normalized differential number counts for AGNs and host star formation at 500 μm for the various star formation scenarios using the composite model. Line colors and styles are the same as in Figure 7. Circles are data points from Herschel (Oliver et al. 2010) and asterisks show the multiply broken power-law model of Glenn et al. (2010). At bright fluxes numerical artifacts are present due to the small number of sources in this flux region.

(A color version of this figure is available in the online journal.)

Figure 13. AGNs and host star formation contribution to the CIRB for the various star formation scenarios using the composite model. Line colors are the same as in Figure 8. The line styles are the same as in Figure 3. Data points are the same as in Figure 5.

(A color version of this figure is available in the online journal.)

The ρᵣ is shown in Figure 14, with the constant star formation model shown as the black lines. The ρᵣ^{ULIRG} is not increased over the bare AGN scenario, however, the total and LIRG AGN infrared luminosity densities are increased slightly. Thus, the constant star formation model does not allow for rapid enough evolution with redshift to match the observed high-redshift ρᵣ.

4.2. AGN Evolution Scenario

It has been suggested that, at least in the quasar regime, the level of obscuration observed in an AGN is connected to
the evolutionary stage of the quasar (e.g., Sanders et al. 1988; Page et al. 2004; Ballantyne 2008; Draper & Ballantyne 2010). Galaxy merger simulations support the evolutionary scenario showing that gas rich mergers lead to a burst of star formation and intense, highly obscured black hole growth (e.g., Hopkins et al. 2006). In the AGN evolution scenario, high Eddington ratio CT AGNs would be expected to have SFRs reaching into the ULIRG regime, and type 2 AGN hosts would be expected to have more star formation than type 1 AGN hosts (e.g., Page et al. 2004). Following this prescription we set the high Eddington ratio CT AGNs to have SFR = 175 M⊙ yr⁻¹, the type 2 SFR = 2.0 M⊙ yr⁻¹, and type 1 SFR = 0.5 M⊙ yr⁻¹. The low Eddington ratio CT AGNs are also given SFR = 0.5 M⊙ yr⁻¹ as these are weak AGNs most likely obscured by molecular clouds in the host bulge or by dust lanes in the host galaxy (Martínez-Sansigre 2009), and not by intense nuclear star bursts. This star formation scenario gives predictions which are only negligibly different from the scenario where all AGNs have SFR = 1.0 M⊙ yr⁻¹ except for the high Eddington ratio CT AGNs which have SFR = 175 M⊙ yr⁻¹.

The Euclidean normalized differential number counts for the AGN evolution scenario are shown as the green lines in Figures 7–12. At all wavelengths the number counts rise as the flux level increases, leveling off around 1 mJy, and then continue to rise at least until the flux level of 10 mJy. CT AGNs dominate at flux levels greater than ~6 mJy and type 2 AGNs dominate at lower flux levels for all wavelengths.

In Figure 13, the AGN contribution to the CIRB for the AGN evolution scenario is shown in green. At 160 μm, AGNs contribute ~6% of the CIRB. CT AGNs dominate the AGN contribution to the CIRB at wavelengths greater than ~200 μm and type 2 AGNs dominate below 200 μm. The peak of the AGN contribution to the CIRB is roughly at the same wavelength as the peak of the CIRB.

The green lines in Figure 14 show the $\rho^{\text{AGN}}_{\text{IR}}$ for the AGN evolution scenario. The total $\rho^{\text{IR}}$ is in decent agreement with observations except at the highest redshift bin, which this model underpredicts. The local $\rho^{\text{LIRG}}_{\text{IR}}$ and $\rho^{\text{ULIRG}}_{\text{IR}}$ are overpredicted by this model but are in good agreement with observations at higher redshifts. However, the $\rho^{\text{ULIRG}}_{\text{IR}}$ observations show a stronger redshift evolution than predicted by this model.

### 4.3. Evolution with Redshift

Also considered was the star formation redshift evolution found by Serjeant et al. (2010), where SFR $\propto (1.0 + z)^{2.3}$. Serjeant et al. (2010) did find that the highest luminosity quasars had a much stronger redshift evolution, perhaps as strong as SFR $\propto (1.0 + z)^{10}$. For simplicity the total volume-averaged SFR redshift evolution is used here, independent of the object luminosity. The local SFR is set such that SFR($z = 0.0$) = 0.5 $M_\odot$ yr⁻¹, in keeping with the average type 1 SFR found in a sample of local Sloan Digital Sky Survey quasars by Kim et al. (2006). Following the unified scheme, the SFR is not dependent on spectroscopic type.

As shown by the red lines in Figures 7–12, the Euclidean normalized differential number counts increase with increasing flux level until peaking at ~1 mJy. The number counts decrease at flux levels above ~1 mJy, and, for wavelengths greater than 160 μm, the number counts decrease more steeply as the wavelength increases. CT AGNs dominate the counts on the brighter side of the peak and type 2 AGNs dominate the lower flux level side of the peak.

The star formation redshift evolution model contribution to the CIRB is shown in red in Figure 13. The AGN contribution to the CIRB at 160 μm is ~5%. CT AGNs dominate the AGN contribution to the CIRB at wavelengths greater than ~100 μm, with type 2 AGNs dominating at lower wavelengths. The AGN contribution to the CIRB for this model peaks at ~320 μm, a significantly longer wavelength than the peak of the CIRB as a whole.

The $\rho^{\text{LIRG}}_{\text{IR}}$ and $\rho^{\text{ULIRG}}_{\text{IR}}$ for the star formation redshift evolution model are very similar to those for the constant star formation scenario, as shown by the red lines in Figure 14. The total $\rho^{\text{IR}}$ of the star formation redshift evolution model underpredicts the observed local $\rho^{\text{IR}}$ but evolves more strongly with redshift than the constant star formation scenario.

### 4.4. Evolution with Redshift and AGN $L_X$

The final star formation scenario investigated here is the redshift and AGN $L_X$ dependent star formation scenario used by Wilman et al. (2010), where

$$\text{SFR} \propto \sqrt{L_X/10^{45}} (1.0 + z)^{1.6}. \quad (7)$$

Type 1 AGNs are given the normalization constant 0.63 $M_\odot$ yr⁻¹ and for type 2 AGNs the normalization prefactor is increased to 2.0 $M_\odot$ yr⁻¹ (Wilman et al. 2010). High Eddington ratio CT AGNs are given the type 2 SFR and low Eddington ratio CT AGNs are given the type 1 SFR, for the reasons discussed in Section 4.2.

The Euclidean normalized differential number counts for the redshift and AGN $L_X$ dependent SFR model are shown as blue lines in Figures 7–12 and are in decent agreement with the predictions made by Wilman et al. (2010) based on a simulation of the extragalactic radio sky. The differential number counts increase with increasing flux level until peaking at 1–3 mJy, depending on wavelength. The peak of the number counts appears to increase with wavelength, with the peak at ~1 mJy at 100 μm and ~3 mJy at 350 μm. The number counts decrease from the peak to the brighter flux levels. At 100, 350, and 500 μm CT AGNs dominate the number counts on the brighter side of
the peak, but at 70, 160, and 250 μm type 2 AGNs dominate except for at the brightest flux levels, \( \gtrsim 10 \) mJy.

The blue lines in Figure 13 show the AGN contribution to the CIRB for the redshift and AGN \( L_X \) dependent SFR model. This model predicts that \( \sim 5\% \) of the CIRB at 160 μm is due to AGNs. Type 2 AGNs dominate the AGN contribution to the CIRB at all wavelengths, and CT AGNs make a significant contribution. For this model, the AGN contribution to the CIRB peaks at \( \sim 300 \) μm, which is significantly different from the peak of the total CIRB around 160 μm.

In Figure 14, the \( \rho_{IR} \) for the redshift and \( L_X \) dependent SFR model is shown in blue. This model is in decent agreement with the \( \rho_{ULIRG} \) at all redshifts but overpredicts the local \( \rho_{ULIRG} \) and underpredicts the local total \( \rho_{IR} \). Both the total \( \rho_{IR} \) and \( \rho_{ULIRG} \) predictions are in agreement with observations at moderate redshifts, but do not evolve strongly enough with redshift to be in agreement with observations at the highest redshift.

5. DISCUSSION

We have presented predictions for observations of AGNs and AGN hosts in the FIR Herschel bands based on the composite model by Draper & Ballantyne (2010). These findings demonstrate that while AGNs may not contribute a large fraction of the CIRB, AGNs will be significant FIR sources and care must be taken in FIR surveys to identify AGNs as such. Here, we discuss the implications of these results in terms of AGNs and AGN host demographics.

5.1. CT AGNs

A substantial population of CT AGNs are necessary for AGN population synthesis models to match the peak of the CXRB at \( \sim 30 \) keV (e.g., Ballantyne et al. 2006a; Treister et al. 2009a; Draper & Ballantyne 2010). Due to the extreme levels of obscuration in CT AGNs, these elusive sources are generally only observed in the very hard X-ray, > 10 keV, or the infrared, especially the FIR. Using X-ray stacking methods, it has been shown that a large fraction of bright infrared excess sources (\( f_{25}/f_R > 1000 \)) host heavily obscured AGNs (e.g., Daddi et al. 2007; Fiore et al. 2009; Treister et al. 2009b). However, it is uncertain how many of these highly obscured AGNs are actually CT (see Georgakakis et al. 2010; Georgantopoulous et al. 2011). Also, there is much debate over the prevalence of AGNs in sources with more moderate infrared luminosities (e.g., Dey et al. 2008; Donley et al. 2008; Fiore et al. 2009; Treister et al. 2009b, 2010). Because CT AGNs are generally not observable in the 2–10 keV band, AGN hard X-ray luminosity functions do not include CT AGNs, and therefore they must added in by hand to population synthesis models. In the population synthesis model used in this study, CT AGNs are assumed to be accreting either at \( L/L_{Edd} > 0.9 \) or \( L/L_{Edd} < 0.01 \), with \( f_{CT} \) independent of \( f_Z \), as found by Draper & Ballantyne (2010). Here, we discuss predictions specifically for CT AGNs in the FIR.

At all wavelengths and for all star formation scenarios, the differential number counts are dominated by CT AGNs for fluxes \( \gtrsim 1–10 \) mJy. Type 2 AGNs dominate at lower fluxes. Moreover, CT AGNs should constitute a non-trivial fraction of Herschel sources. Depending on the star formation scenario considered, CT AGNs could make up \( \sim 10\% \) of Herschel sources, even at 500 μm.

Depending on the star formation scenario, CT AGNs are found to contribute <5% of the CIRB at 160 μm. For bare AGNs, CT AGNs dominate the AGN contribution to the CIRB at wavelengths \( \gtrsim 200 \) μm. When star formation is included, CT AGNs dominate the AGN contribution to the CIRB at wavelengths \( \gtrsim 100 \) μm for all star formation scenarios, except the Wilman et al. (2010) model.

Comparing the predictions made here against the infrared luminosity density found by Le Floc’h et al. (2005), we find that CT AGNs and their hosts contribute \( \sim 3\% \) of the local infrared luminosity density from sources with \( L_{IR} > 10^{10} L_\odot \) and nearly one-fourth of the infrared luminosity density from sources in the ULIRG range. In the AGN evolution star formation scenario, CT AGNs can account for all of the local ULIRG range luminosity density. At \( z \sim 1 \), the relative CT AGN contribution decreases significantly in all luminosity ranges. However, when taking into account the stronger evolution of the SFR in high-luminosity sources found by Serjeant et al. (2010), CT AGNs and their hosts can still contribute nearly a quarter of the infrared luminosity density in the ULIRG range at \( z \sim 1 \). Showing that at higher redshifts CT AGNs contribute less to the total infrared luminosity density, but may still contribute quite significantly to the brightest sources.

The FIR is an important wavelength range for observing CT AGNs due to the large amount of cold dust which obscures CT AGNs. The majority of AGNs observed by Herschel will be CT. Depending on the star formation trends in CT AGN hosts, CT AGNs and their hosts may constitute nearly \( \sim 10\% \) of Herschel sources at 500 μm. The relative contribution of CT AGNs and their hosts to the ULIRG range infrared luminosity density is \( \lesssim 25\% \) and appears to be approximately constant over the redshift range \( z = 0–1 \). However, Hatziminaoglou et al. showed that AGNs cannot be identified by their Herschel-SPIRE colors alone. Therefore, finding CT AGNs in the FIR will require either Spitzer-MIPS coverage of bright SPIRE sources (Hatziminaoglou et al. 2010) or X-ray stacking. Since the AGNs and host differential number counts for both the composite and original models are dominated by CT AGNs in the SPIRE bands, X-ray stacking of bright SPIRE sources is likely to disclose a large fraction of the CT AGN population.

5.2. Differences Between Original and Composite Model

The difference between the original model and the composite model is that in the composite model the CT AGNs are put in specific, physically motivated Eddington ratio bins. Also, in the original model \( f_{CT} \propto f_Z \), but in the composite model \( f_{CT} \) is independent of \( f_Z \). In order to understand the effects of the differences between the two models, we compare the predictions of the original and composite model for the constant star formation scenario.

In the differential number counts, the differences between the composite and original models are small but not insignificant. At all wavelengths the original model has a steeper decline in the bright end counts than the composite model. The original model predicts that the number counts will be dominated by type 2 AGNs except for at the brightest fluxes. Conversely, in the composite model the differential counts are dominated by CT AGNs at every wavelength for fluxes \( \gtrsim 1 \) mJy.

The original model predicts a smaller overall AGN contribution to the CIRB than the composite model. In the composite model, CT AGNs dominate the AGN contribution to the CIRB at wavelengths greater than 100 μm, but in the original model

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5 Models are available in table form by contacting the authors.
the type 2 AGNs dominate the AGN contribution to the CIRB at all wavelengths.

The original and composite models make similar predictions as to the AGN contribution to the infrared luminosity density in all luminosity ranges. The difference between these two models is most noticeable in the contribution of CT AGNs to the local ULIRG range luminosity density. The original model predicts that CT AGNs contribute 4% of the local ULIRG infrared luminosity density. The composite model predicts that nearly one-fourth of the local ULIRG infrared luminosity density is due to CT AGNs.

The overall predictions of the original and composite models are in agreement. To observationally determine which model best describes the CT AGN population, rigorous measurements of the CT AGN contribution to the local infrared luminosity density and/or accurate accounting of Herschel number counts to see whether CT AGNs or type 2 AGNs dominate the number counts will be needed.

5.3. Star Formation in AGN Hosts

As seen in Figures 7–12, the star formation scenario used greatly affects the predicted differential number counts. At wavelengths $\leq 250\,\mu m$, the faint end slope is similar for all the star formation models investigated here, but the bright end slope is highly dependent on the host star formation at all wavelengths. The differences between the various star formation scenarios become more prominent when observing at longer wavelengths. The constant star formation model peaks at $\sim 1$ mJy and has a relatively flat bright end slope. The AGN evolution star formation model peaks at $\geq 10$ mJy with a knee at $\sim 1$ mJy. The redshift-only evolution model peaks around or just short of 1 mJy. This model also has the steepest faint and bright end slopes of the star formation scenarios considered here. The Wilman et al. (2010) star formation model peaks between 1 and 10 mJy for wavelengths $\geq 100\,\mu m$. The flux level of the peak in the differential counts may be an important tool in understanding the evolution of SFR in AGN hosts. This tool will be most effective when observing at longer wavelengths.

Dust obscured star formation is believed to be the primary progenitor of the CIRB with much debate as to the contribution from AGNs. Ballantyne & Papovich (2007) found that AGNs and star formation in AGN hosts can account for $\sim 30\%$ of the CIRB at 70 $\mu m$. Similarly, Mullaney et al. (2010) find that AGNs contribute $5\%$–$25\%$ of the CIRB at $70\,\mu m$. However, at longer wavelengths it appears that the AGN contribution reduces to $\lesssim 10\%$ (Jauzac et al. 2011; Lacey et al. 2010). In this work it was found that AGNs and host star formation contribute $\sim 5\%$ of the CIRB at $160\,\mu m$. However, when investigating the submillimeter properties of X-ray-selected AGNs, Lutz et al. (2010) found the average AGN SFR to be $\sim 30\, M_\odot \, yr^{-1}$, in which case AGNs and their hosts would contribute $\sim 88\%$ of the CIRB at $160\,\mu m$. Therefore, understanding the star formation trends in AGN hosts is necessary for understanding how significant the contribution of AGNs and their hosts is.

The peak intensity of the CIRB occurs at $\sim 160\,\mu m$. The star formation scenarios investigated here which take into account the evolution of the SFR with redshift predict that the peak of the AGN contribution to the CIRB occurs at $\sim 300\,\mu m$. This suggests that the SFR of AGN hosts evolves differently with redshift than the SFR of normal galaxies. This effect could also be explained if the star formation SEDs used here are on average too cold, which is unlikely. If it is true that the SFR of AGN hosts evolves differently than the SFR of normal galaxies, this could offer important insights into the role of the AGNs in the host galaxy evolution. At wavelengths shorter than the peak of the CIRB, the dominant contribution is from sources $z < 1$. Sources at $z > 2$ tend to dominate at wavelengths longer than $500\,\mu m$.

Another tool used to study different AGN host star formation scenarios is the infrared luminosity density. Using simulations, Hopkins et al. (2010) find that AGNs contribute 1%–5% of the total infrared luminosity density at all redshifts. Applying the classification scheme of Yuan et al. (2010) to AKARI sources, Goto et al. (2011) find that AGNs contribute $\sim 20\%$ of the total infrared luminosity density, $\sim 40\%$ of the luminosity density from sources in the LIRG range, and $\geq 90\%$ of the luminosity density of sources in the ULIRG range, regardless of redshift. When considering the infrared luminosity density as measured by Le Floc’h et al. (2005), we find that the AGN and host galaxy contribution to the local infrared luminosity density is approximately a factor of two smaller than that found by Goto et al. (2011). At $z \sim 1$ the relative AGN contribution decreases to $\lesssim 5\%$ for all luminosity ranges. Even when taking into account the stronger evolution of the SFR in high-luminosity sources found by Serjeant et al. (2010), it appears that AGNs and their hosts only contribute $\sim 25\%$ of the infrared luminosity density in the ULIRG luminosity range at $z \sim 1$. The reduction in the AGN contribution to the ULIRG range infrared luminosity density by a factor of two between $z \sim 0$ and $z \sim 1$ is consistent with the findings of Sturm et al. (2010) that ULIRG level luminosities can be achieved without major mergers at higher redshifts, suggesting that the AGN fraction in the high-redshift ULIRG population will be smaller than that found locally.

Determining the star formation history of AGN hosts is important in understanding why some galaxies host active supermassive black holes (SMBHs) and other galaxies host inactive SMBHs. The predictions presented here show that the flux level of the differential number counts peak in longer wavelength bands will be a helpful tool in determining the star formation history of AGN hosts. By comparing the peak wavelength of the AGN contribution to the CIRB to the peak wavelength of the CIRB, it is possible to determine if the star formation evolution of AGN hosts is different from that of normal galaxies. Also, at higher redshift AGNs will have a smaller contribution to the ULIRG population and that contribution will be dominated by CT AGNs.

5.4. Eddington Ratio Breakdown

By using $d\Phi_{\lambda}(L_X, z)/d \log L_X$, the evolving Eddington ratio space density computed by Draper & Ballantyne (2010), instead of a traditional luminosity function, it is possible to make predictions for the contribution of AGNs with different Eddington ratios. In Figures 15 and 16, the composite model Euclidean normalized differential counts are shown for the AGN evolution star formation model at 160 and 500 $\mu m$ with the relative contributions from the different Eddington ratio bins shown. The blue lines show the contribution from AGNs with $L/L_{\text{Edd}} < 0.01$. The green lines show the contribution from AGNs with $0.01 < L/L_{\text{Edd}} < 0.9$. The contribution from high Eddington ratio sources is shown in red. For all but the AGN evolution scenario, the number counts are dominated by low Eddington ratio AGNs at all flux levels, due to the high space density of low accretion rate AGNs at all redshifts. As shown in Figures 15 and 16, the AGN evolutionary scenario bright end counts are dominated by high Eddington ratio CT AGNs because of the high SFR in these objects.
For all star formation scenarios the low Eddington ratio sources dominate the AGN contribution to the CIRB at wavelengths \(\gtrsim 100\ \mu m\). The AGN contribution to the infrared luminosity density is dominated by moderate Eddington ratio AGNs at all luminosity levels for all star formation scenarios except the AGN evolution star formation model, where the high Eddington ratio sources dominate the ULIRG range. The star formation scenarios that do not include redshift evolution find that low Eddington ratio sources dominate the AGN contribution to the local infrared luminosity density.

5.5. Implications for Herschel and ALMA

The three wide area surveys conducted by Herschel will yield a large catalog of AGN host galaxies. Using the planned survey depths and areas as described in Section 1, the models discussed here predict the following numbers of AGN hosts to be observed by the Herschel wide field surveys. Not including the planned lensing cluster observations, PEP should observe 100–500 AGN hosts, depending on the star formation scenario, at 160\(\mu m\) with 5\(\sigma\) significance. The portion of HerMES conducted during the Herschel science demonstration phase should provide 140–2100 AGN hosts, depending on the star formation scenario, with 5\(\sigma\) significance at 350\(\mu m\). The H-ATLAS survey will yield 250–4000 AGN hosts at 160\(\mu m\) and 90–1200 AGN hosts at 350\(\mu m\) with 5\(\sigma\) significance. The H-ATLAS observed AGN hosts counts drop to 30–230 in the 500\(\mu m\) band. This catalog of sources will provide a robust sample to better constrain the star formation properties of AGN hosts.

Hatziminaoglou et al. (2010) showed that AGNs cannot be differentiated from normal galaxies based only on their FIR colors; therefore, ALMA will only be able to offer supplementary data on AGNs which are identified in other wavelength bands. The wide area surveys conducted by Herschel will provide many promising candidate targets for ALMA. The dotted gray lines in Figures 11 and 12 show the sensitivity limit of the 350 and 450\(\mu m\) ALMA bands, respectively, as quoted in Section 1. Based on this projected sensitivity and the models presented here, the areal density of AGN hosts available to ALMA at 450\(\mu m\) will be 300–1500 deg\(^{-2}\), depending on the star formation scenario, for an integration time of only 60 s. Therefore, using ALMA to conduct follow-up observations on X-ray-selected AGNs should be an efficient way to study star formation in AGN host galaxies. As discussed in Section 5.3, the differential number counts for different star formation scenarios seem to peak at different flux levels. These peak fluxes become more differentiated at higher wavelengths. By providing deeper submillimeter observations of Herschel sources and X-ray-selected AGNs, ALMA should be able to determine the evolution of star formation in AGN hosts. This will allow the determination of the wavelength where the AGN contribution to the CIRB peaks, and therefore whether the star formation in AGN hosts evolves differently than in normal galaxies. Furthermore, since ALMA will be taking spectra, measurements such as gas velocity, abundances, and temperature can be made. This will allow ALMA to not only determine the evolution of star formation in AGN hosts, but also to probe the physical structure of AGN host galaxy star formation.

5.6. Evolution of AGNs

From deep X-ray surveys it is known that high-luminosity quasars and moderate luminosity AGNs evolve differently with respect to redshift (e.g., Ueda et al. 2003). This would suggest that quasars and Seyferts are caused by processes with different timescales. Also, it appears that the Seyfert population is well described by the unified scheme, but the high-luminosity AGN...
population may not follow the unified model (e.g., Ballantyne et al. 2006b; Lutz et al. 2010). A picture is starting to surface where the most powerful AGNs are triggered by major mergers as explored in the simulations by Hopkins et al. (2006) and others, but most AGNs are triggered by less violent processes (Ballantyne et al. 2006a). This picture is taken into account here by using the composite model of Draper & Ballantyne (2010) to describe the CT AGN fraction as Eddington ratio dependent. The difference in triggering process will also affect the star formation within the host galaxy. Mergers will engender not only AGN activity but also bursts of star formation. Contrastingly, the secular evolution experienced by moderate power AGNs is expected to be accompanied by steady, moderate star formation.

This AGN evolution scenario was further explored here with the AGN evolution star formation scenario. In this scenario, high Eddington ratio CT AGN hosts were assigned SFR = 175 $M_\odot$ yr$^{-1}$. The differential counts for this star formation scenario show a large peak $\gtrsim$10 mJy. However, the high Eddington CT AGNs account for $\approx$100% of the local ULIRG range infrared luminosity density measured by Le Floc’h et al. (2005). If the SFR in high Eddington ratio CT AGN hosts is reduced to $\sim$100 $M_\odot$ yr$^{-1}$, then AGNs will contribute 80% of the local ULIRG range infrared luminosity density, with a larger contribution to the local LIRG range infrared luminosity density. The prominent peak in the differential counts at $\sim$10 mJy persists, despite the reduced SFR in high Eddington ratio CT AGNs. Therefore, a test of the AGN evolution scenario will be if the observed differential counts feature a strong bright end peak, possibly with a knee at moderate fluxes. As a large fraction of the sources contributing to this peak will be CT AGNs, the AGN samples used for this test will have to be chosen very carefully.

6. SUMMARY

FIR observations by telescopes such as Herschel and ALMA will provide important insights into many questions about AGNs and their hosts. Determining the flux level at which the differential AGNs and host number counts peak will offer crucial constraints to the star formation history of AGN hosts, especially when observing at wavelengths at $\sim$500 $\mu$m. The predictions presented here show that it is likely that the SFR in AGN hosts evolves differently than the SFR in normal galaxies, as indicated by the peak wavelength of the AGN contribution to the CIRB being significantly longer than the peak wavelength of the CIRB. Understanding how the SFR evolution in active galaxies differs from quiescent galaxies will provide clues on the triggering mechanisms of AGNs and how the AGN interacts with the host galaxy. FIR observations will also allow the AGN evolution scenario to be tested by comparing SFRs in bright AGNs with different levels of obscuration. The relative contributions of AGNs with various levels of obscuration to the bright end differential counts will also be an important test of the major merger trigger model. Applying X-ray stacking techniques to bright 350 or 500 $\mu$m sources, especially sources with a hot dust component in the SED, will be an efficient way of finding CT AGNs.

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13
