Revisiting the Torus: Spectral Predictions from the IR to the X-ray

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Absorbing gas along the line of sight to an AGN is most often probed by either X-ray or infrared observations. However, the effects of dust are frequently ignored in the X-ray analysis; likewise, the infrared data are often interpreted with little thought to the physical interactions between the dust grains and the gas. In this contribution, we present preliminary work on our calculations of the spectral energy distributions (SED) of irradiated dusty gas in an AGN environment. The interactions between the gas and the dust is treated (almost) self-consistently, so the SED is complete from the far-infrared to the hard X-rays. In their final form, these SEDs will be useful to compare against new joint SIRTF/Chandra observations of AGN.

1. INTRODUCTION

Circumnuclear obscuring material is the cornerstone of the unified model of active galactic nuclei (AGN), where the differences between the type 1 sources (those which show both broad and narrow optical emission lines) and the type 2s (those which exhibit only narrow lines) are almost entirely due to the viewing angle into the nucleus. Despite the importance of this absorbing gas to our understanding of AGN, almost nothing is known about its geometry, location or physical conditions. Based on the observed ratio of Seyfert 1s to Seyfert 2s (although this is a difficult number to determine), a large, geometrically thick toroidal structure is often inferred for the obscuring matter [1]. However, alternatives such as a warped or flared disk [2] or a clumpy ring [3] are also viable.

Observationally, there are few direct probes of the absorber. VLBI megamaser observations can reach the small scales needed to probe the nuclear environment (i.e., $\sim$ 0.1–1 pc from the central engine), and have found evidence for both warped disks [4,5] and toroidal structures [6]. However, maps of strong maser sources are rare, and do not provide an unbiased sample of active galaxies. Other clues to the obscuring matter are obtained in the infrared (IR) and X-ray continua from AGN. X-ray observations can constrain the total column of absorbing gas along the line of sight by measuring the soft X-ray cutoff in the nuclear spectrum. Seyfert 1s typically show much lower intrinsic column densities than Seyfert 2s, consistent with the unification hypothesis. The absorbing columns measured in Seyfert 2s tend to be $\sim 10^{23-24}$ cm^{-2} [7], which could be the column through the torus. The energy absorbed by this material will be reradiated elsewhere, and indeed most AGN exhibit strong near infrared (NIR) emission peaking between 3 and 10 μm, with a dip around 1 μm and a rapid fall off above 100 μm [8,9]. These properties are indicative of thermal dust emission with temperatures ranging from $\sim$ 40 K up to the sublimation temperature of 1000–2000 K. The sublimation radius for an average grain is $\sim$ 1 pc [10], and so the hottest dust is well placed to obscure sightlines into the broad-line region. This distance is also supported by the narrow and neutral Fe Kα lines observed in the X-ray spectra of many AGN. In the cases where the line has been resolved by the *Chandra* gratings, the FWHM indicates a distance consistent with the broad-line region or beyond [11]. At face value, these observational facts imply that the obscuring material is cold (from the X-ray absorption and emission properties) and dusty, and is distributed in a geometrically thick configuration about 1 pc from the nucleus. Yet, dust emission models fit to the observed IR spectral energy distributions (SEDs) of AGN have also shown problems with the standard toroidal model. These models require a large-scale distribution of dust, not a compact thick geometry [9,12].

These studies have concentrated only on the dust emission, but the grains are closely tied to the gas. While it has long been understood that hot gas will alter the properties of any associated dust grains [13], the fact that hot dust will significantly affect the associated gas is less appreciated. With the launch of SIRTF, there is the exciting possibility of simultaneous IR, optical and X-ray observations of AGN, which will give high signal-to-noise, simultaneous SEDs. Here, we use the latest version of Cloudy to calculate the spectra predicted from the heated dust layer, including the effect of the gas. This should be useful for comparing with future observations, and as a guide for further, more detailed modeling.

2. CALCULATIONS

The latest version of the photoionization code Cloudy was used to calculate the thermal and ionization structure of a dusty cloud subject to a hard ionizing continuum. The code uses a new, more physical grain model where the size distributions of both the silicate and graphite components are each resolved into any number of individual bins, which are then treated separately throughout the calculation. The grain physics has also been updated to incorporate the results on grain-gas interactions by [14]. In particular, a more sophisticated treatment of photoelectric emission and electron capture are used to calculate gas heating rates and the total charge of the grains. The new dust module in Cloudy also takes into account the non-equilibrium temperature spiking which is important for very small grains. Further details on the new treatment of dust in Cloudy can by found in the paper by [15].

The models were parameterized by only two numbers: the constant hydrogen number density of the cloud ($n_{\rm H}$) and the energy density temperature of the incident radiation field (T_U). Grains are efficient (but not perfect) absorbers and emitters, and their temperatures usually are slightly above T_U. The geometry was plane-parallel, and the total hydrogen column density for each cloud was fixed at 10^{23} cm^{-2}, typical for what is observed in a Compton-thin Seyfert 2 [7]. Typical HII region grain sizes (minimum radius of 0.03 μm; maximum radius of 0.25 μm) and gas-phase abundances were used in all models. Both astronomical silicate and graphite were included with a dust to gas ratio (by mass) of 6.418×10^{-3}.

Models were run for $2 \leq \log n_{\rm H} \leq 7$ (with $\Delta \log n_{\rm H} = 1$) and $T_U = 30, 60, 120, 240, 480$ and 960 K. Two different ionizing continua were used. The first was a broken power-law which has a spectral index of $\alpha = 2.5$ (so that $f_\nu \propto \nu^\alpha$) below 10 μm, $\alpha = -1$ between 10 μm and 50 keV, and $\alpha = -2$ above 50 keV. The second continuum is a toy AGN spectrum with a big blue bump, parameterized by its temperature, and a high energy power-law. We chose a bump temperature of 1.4×10^5 K, the maximum accretion disk temperature for a 10^7 M$_\odot$ black hole accreting at 0.1 of its Eddington rate, and a hard power-law of $\alpha = -0.9$. The X-rays were normalized to the optical/UV by setting $\alpha_{ox} = -1.4$. Both continua are plotted as dotted lines in Figure 1 below.

3. PRELIMINARY RESULTS

We show four example SEDs from the calculations in Fig. 1. In each panel, the solid line plots the spectrum emitted from the illuminated face of the cloud (i.e., the reflected emission), the dashed line shows the transmitted spectrum, and, as mentioned above, the dotted lines plot the incident ionizing continuum. Therefore, the sum of the dotted and solid lines would correspond to the case where an observer can view the nuclear emission directly (i.e., a type 1 AGN), while the dashed line (plus the unmodeled narrow-line emission, and any scattered radiation) would be observed in a type 2 object. All the models shown

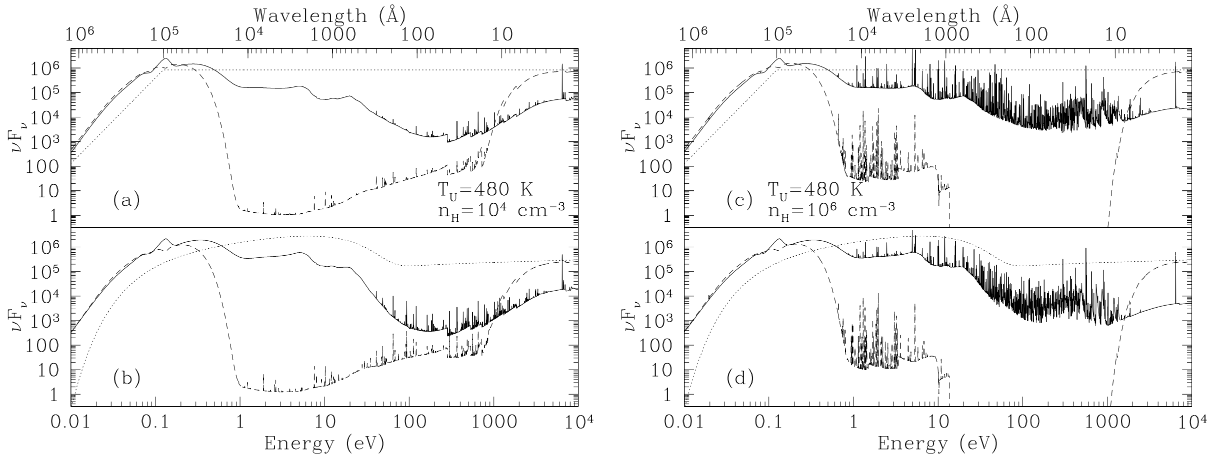

Figure 1. Reflected (solid), incident (dotted) and transmitted (dashed) spectra predicted by Cloudy for two different physical conditions: $n_{\rm H} = 10^4$ cm^{-3} and $T_U = 480$ K (left), and $n_{\rm H} = 10^6$ cm^{-3} and $T_U = 480$ K (right). Plots (a) and (c) show the results using the power-law continuum, while the spectra computed with the AGN-like continuum are shown in (b) and (d).

have $T_U = 480$ K, which results in dust temperatures at the surface of the cloud of ~ 1000 K (see Figure 2), below the sublimation temperature. As a result, the model SEDs show strong NIR emission, peaking around 3 μm as observed [12]. The two left-hand panels show models run with $n_{\rm H} = 10^4$ cm^{-3}, with the resulting cloud being ~ 10 pc deep, while the right-hand panels consider models with $n_{\rm H} = 10^6$ cm^{-3}, and thus have pathlengths of ~ 0.1 pc.

The gas in the models with the lower density of $n_{\rm H} = 10^4$ cm^{-3} are highly ionized (note the lack of H Lyα absorption which is very apparent in the $n_{\rm H} = 10^6$ cm^{-3} transmitted SED). Yet, the transmitted spectrum still exhibits strong absorption in the soft X-ray and extreme ultra-violet due to the hot dust. Two other features of note in the reflected spectrum are a 10μm bump from the silicate grains (whether or not this has been observed is the subject of some controversy), and a neutral, narrow Fe Kα line which for the low density models results entirely from fluorescence of the iron in the silicate grains.

The importance of the grains to the temperature of the irradiated gas is shown in Fig. 2, where we plot both the grain and gas temperatures as a function of depth into the $n_{\rm H} = 10^6$ cm^{-3}, $T_U = 480$ K cloud. The figure shows that suppressing the heating effects of the dust decreases the gas temperature at the outer part of the cloud by about an order of magnitude from where it was with the effects of grain heating included. This large drop results from the fact that photoelectric heating is $> 95\%$ of the total local heating rate in the ionized zones (dotted line and right-hand axis in Fig. 2). The temperature is slightly higher when grains are removed entirely as the lower opacity allows more of the gas to be ionized.

One consistency problem with these results is that they do not yet take into account sputtering of the grains by the hot gas. If sputtering is important then the dust will be short-lived and the gas will cool down closer to the 'no grains' solution seen in Fig. 2. Furthermore, the photoelectric heating rate is a strong function of the grain size [16], so if there are no small grains in the nearby environment of an AGN (as proposed by [17]), then this should have an impact on the predicted SEDs. However, the sputtering rate will

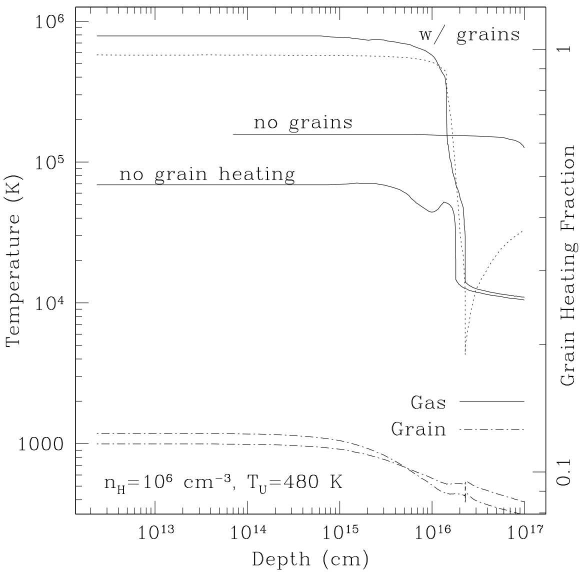

Figure 2. The temperature structure of the $n_{\rm H} = 10^6$ cm^{-3}, T_U = 480 K cloud. The dot-dashed lines show the dust temperature with the upper and lower lines denoting the smallest silicate and graphite grains (0.03 μm), respectively. Both species are below their sublimation temperatures. The solid lines show the gas temperatures for different grain treatments. The temperature of the cloud when grain-gas heating is artificially suppressed is shown by the lower solid line. Removing grains entirely results in the temperature profile denoted by the middle solid line (the lower opacity means that there are larger jumps in depth for each zone). However, the hottest gas is found when grains are included, as photoelectric heating by grains is $> 95\%$ of the total heating rate (dotted line and right-hand axis).

depend on the grain charge (the higher the grain charge, the harder it is for a fast moving gas ion to overcome the barrier and collide with the grain), which is largely unknown for the high energy radiation fields considered here. Therefore, our current work is to understand the amount of grain charging expected and its impact on the sputtering rate. Once that is completed, we will be in the position to self-consistently compute the SED of a dusty absorber from the FIR to the hard X-ray. This will ultimately lead to a better understanding of its geometry and its place within the AGN environment.

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