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DUSTY DISKS AND THE INFRARED EMISSION FROM AGN

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ABSTRACT. The distortions inferred in the gaseous disks of active galaxies suggest that a significant, and possibly dominant fraction of the 1-1000 μm radiation observed from AGN must be thermal emission from gas and dust heated by the central source. We report calculations of the growth and sublimation of dust grains in the outer parts of accretion disks appropriate to AGN. The thermal state of the gas undergoes a sudden change at the radius where the dust sublimates. The outer portion of the accretion disk radiates at 0.5-5 μm; free-free emission from gas whose dust has sublimated contributes to the flux at 0.5-2 μm. If this thermal emission dominates the flux from radio-quiet quasars, it naturally explains the frequency and depth of the universal minimum in νF_ν at $10^{14.5}$ Hz. Free-free emission from the photoionized surface layers of the disk at larger radii produces a radio flux at $\nu \lesssim 10^{11}$ Hz comparable to that observed in radio-quiet quasars. The far-infrared and submillimeter emission from radio-quiet quasars and Seyfert galaxies is more naturally interpreted as reradiation by dust, than as nonthermal emission from the inner accretion disk.

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1. INTRODUCTION

It is generally accepted that emission from heated dust produces the steep far-infrared continua of Seyfert 2's and the IRAS warm galaxies. It is also generally acknowledged that the rapidly variable infrared emission in the BL Lacs and optically violently variable quasars must be produced by non-thermal processes. Both thermal and non-thermal emission evidently occurs in nature, in objects of comparable luminosities. The controversy over the nature of the emission in radio-quiet quasars is thus not over whether either emission process is physically possible or plausible. Both are, and both are probably present at a significant level in all objects. The question is simply which happens to predominate in radio-quiet quasars.

In most optically selected quasars, the 1-100μ infrared luminosity comprises 10-50% of the bolometric luminosity (Sanders et al. 1989). Since the energy liberated per octave in radius in an accretion disk scales as r^{-1}, the high relative infrared luminosity requires that the ultimate source of energy for the infrared radiation be within a few times the inner radius of the accretion disk. If the infrared radiation is emitted from a region comparable in size to that of its energy source, it must be nonthermal: blackbody limits on the source size at 1 μ and at 60 μ are respectively > 0.1 pc and > 100 pc for the most luminous sources in figure 1a and > 0.003 pc and > 10 pc for the least luminous. If the infrared radiation is thermal, and therefore emitted at large radii, it *must* be reprocessed energy transported to the emission radii by radiation or by mechanical means (e.g., a jet).

Dust heated locally by stars may contribute to some of the infrared emission from quasars. It is unlikely, however, that this dominates in the majority of sources. For stars to produce the typical infrared luminosity of $10^{13}\ L_{\odot} = 0.5\ M_{\odot}\ c^2\ \mathrm{yr}^{-1}$ would require a star formation rate of *at least* 500 $M_{\odot}\ \mathrm{yr}^{-1}$ (this lower limit assumes that only massive O stars are formed; a normal IMF would require a rate approximately 10 times higher). Over the ~ 10^8 yr lifetime of a quasar, > 5 x $10^{10}\ M_{\odot}$ of gas would have to be processed in massive stars. Dust would form from the metals produced. So much gas and dust, pushed to high latitudes by supernova explosions, would inevitably absorb and reradiate much of the luminosity from the central source. But the optical and ultraviolet radiation from quasars, variable on timescales $\lesssim$ 10 yr (Usher 1978) must come from such a central relativistic source. Since its luminosity is comparable to the infrared luminosity, we conclude that reradiation from gas and dust heated by it would necessarily be *at least* comparable to anything contributed by stars. In what follows we therefore ignore the heat input from stars, except insofar as they provide a natural minimum dust temperature $\gtrsim$ 25 K.

Quasars and Seyfert galaxies appear to be located in galaxies amply supplied with interstellar medium. The disks of gas and dust in normal galaxies exhibit warps on all scales, and would intercept and re-radiate ~ 10% of the luminosity from a central source. Several lines of evidence suggest that the warps are even more severe in Seyferts and quasars, so that an even larger fraction of the central luminosity would be reradiated. Provided most of the reradiating material is located in an optically thick disk, the central source will never appear absorbed or reddened - either we have a clear line of sight, or the source is entirely occulted. This picture is thus consistent with the absence of reddening or absorption by broad emission line clouds in quasars.

We describe below the opacities and physical state of gas in the disks at distances from 10^{-3} pc to 10^{4} pc from the central source. Dust grains can form and grow in the disk within 1 pc. At much smaller radii, however, even graphite grains will sublimate. When this occurs, the gas loses its primary coolant, and heats until it reaches a new thermal equilibrium at $\gtrsim 10^{4}$ K. The superposition of emission from radii inside and outside this transition point naturally explains the minimum in $\nu L\nu$ at $\nu = 10^{14.5}$ Hz observed in most quasars. The characteristic scale length of dust in galaxies (~ 2-10 kpc) naturally explains both the frequency and steepness of the drop in $\nu L\nu$ at $\nu = 10^{14.5}$ at $\nu \lesssim 10^{12}$ Hz. The normalization of infrared luminosity relative to the UV and X-ray luminosities of quasars is consistent with expected covering factors and space-densities. Free-free emission from the photoionized zones on the illuminated surfaces of the disk naturally provides a flat-spectrum radio flux comparable to that observed in many quasars (Antonucci & Barvainis 1988), and may contribute to the optical continuum emission. It appears therefore that the emission at wavelengths 1-1000 μm from Seyfert galaxies and quasars other than OVV's is naturally explained as thermal reradiation from the nuclear disk and the interstellar medium of the host galaxy. Although non-thermal emission from the central source may contribute in some objects at some times, a significant contribution from thermal emission seems unavoidable.

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2. DUST AND WARPS

Most previous discussions of dust and gas in the host galaxy of an active nucleus have concentrated on spherically symmetrical distributions of dust (Rees et al. 1969, Bollea & Cavaliere 1976, Barvainis 1987 - the latter also considered conical sectors, or have concentrated on their effects on emission line clouds: Davidson & Netzer 1979, MacAlpine 1985 and references therein). A few have considered disk-like distributions (Begelman, McKee & Shields 1983, Begelman 1985, Shlosman & Begelman 1988), but have assumed the disks were planar and relatively thin, so that they intercepted only a small fraction ($\lesssim$ 1%) of the luminosity of the central accretion disk. Neither of these distributions is very likely. The gas and dust most probably lie in what could crudely be described as a heavily warped (and probably clumpy) disk. Beyond about a kiloparsec radius, the orbital time t_{orb} 10^8 (r / 3 kpc) yr is so long that gas captured or disturbed by a recent interaction with another galaxy will not have had time to settle into the preferred plane of the host galaxy's potential in a quasar lifetime (~ 10^8 yr). Since quasars seem commonly to be involved in interactions or mergers (Hutchings 1983, MacKenty & Stockton 1984), large warps and streamers are to be expected. The warped disk of NGC 5128 (Centurus A) is a famous example. Moving inwards, warps on kiloparsec scales can be produced by counter rotating bars (Vietri 1986), by continuing infall of gas (Ostriker & Binney 1989), and by Kelvin-Helmholtz instability as the disk rotates through a pressure-supported corona (Gunn 1979) Though such warps are difficult to detect in external galaxies which are not nearly edge-on, let alone in quasars, the gas at ~ 3 kpc in our own Galaxy is tilted by about 15° with respect to the plane defined at larger radii (Vietri 1986), and most well-studied Seyfert galaxies have strong kiloparsec-scale bars (Adams 1977).

The same warp-inducing processes can operate on scales of parsecs. The molecular torus extending from 2-8 pc from our Galactic center is tilted by ~ 15° (in the opposite direction from the 3 kpc warp!) with respect to the plane defined by the stars. The parsec-scale dust torus in NGC 1068 (Antonucci & Miller 1985) has its axis at right angles to the kiloparsec-scale disk of gas and stars (Wilson & Ulvestad 1982), and the axes of similar tori inferred to exist in other Seyferts make random angles to the minor axes of the disks of their host galaxies (Unger et al. 1987, Haniff et al. 1988).

We conclude that warps are common and substantial enough to allow the nuclear continuum to illuminate the dust and gas on scales from 1-10^4 parsecs. The broad-line region (BLR) will be obscured by this dust over a range of viewing angles comparable to the covering factor of the dust disk. Except in the case that the narrow line gas is cospatial with the dusty disk in a symmetrical warp, it is difficult to prevent the narrow line region from being visible from some viewing angles when the BLR is obscured. This occurs for a fraction of sky of order the covering factor of the dust disk extending beyond the NLR: typically ~ 0.05-0.1. Since molecular clouds are larger than the 0.1-1 pc scale of the BLR, the same fraction of quasars with obscured broad line regions would be expected even if the dust were in clouds at high latitudes rather than in a disk. These objects would appear as ``quasar-2's'' (by analogy to Seyfert 2's).

Such objects have been rare in optical surveys, but appear common in infrared-selected samples (Sanders et al. 1988b). In radio samples they may masquerade as narrow line radio galaxies (Scheuer 1987, Barthel 1989).

We now examine the state of dust in a warped disk illuminated by the central accretion disk of a quasar, and its possible relevance to the infrared and submillimeter spectra of quasars. We postpone to section 5 a discussion of the vertical structure of an illuminated disk, and the expected optical and radio emission therefrom.

The equilibrium temperature T_g of dust grains of characteristic radius $a \gtrsim 20$ Å at distance r from a radiation source of luminosity density L_ν (erg s^{-1} Hz^{-1}) is determined implicitly by

$$\frac{1}{16\pi r^2}\int_0^\infty L_\nu Q_{abs}(\nu)d\nu = \int_0^\infty \pi B_\nu(T_g)Q_{abs}(\nu)d\nu \quad (1)$$

where Q_{abs} (ν) is the absorption efficiency (cross section in units of πa^2), at frequency ν. Graphite grains with a ~ 0.1 μm are transparent to X-rays with $h\nu$ > 0.4 keV and for 0.1 keV < $h\nu$ < 0.28 keV (K-edge of Carbon), so $Q_{abs}(\nu) \propto a$ at those energies. At wavelengths $\lambda < 2\pi a$ where the grain is not transparent $Q_{abs} \simeq 1$. At longer wavelengths $\lambda > 2\pi a$ the grain becomes a weakly coupled antenna, $Q_{abs} \simeq (2\pi a / \lambda) f(\lambda)$ where $f(\lambda)$ depends on the dielectric tensor and shape of the grains (fits for various grain compositions and shapes, and discussion of the Mie scattering range can be found in Martin 1978, Draine & Lee 1984, Wright 1987, and references therein). Observations of galactic dust indicate that outside resonances $f(\lambda) \propto \lambda^{1-\alpha}$, with $1 \lesssim \alpha \lesssim 2$ (Whittet 1988).

In quasars, most of the energy from the central source is emitted at frequencies for which Q_{abs} (ν) $\simeq$ 1, and reradiated at wavelengths $\lambda > 2\pi a$. Hence if we ignore heating and cooling of grains by collisions with atoms (generally weak), the temperature of directly illuminated grains is given approximately by

$$\frac{L}{16\pi r^2} \simeq \sigma T_g^4 \langle Q_{abs}(T_g)\rangle \qquad (2)$$

where $< Q_{abs}(T) >$ is the Planck-averaged absorption efficiency (cf. Draine 1981), $< Q_{abs}(T) > \propto T_g{}^\alpha$. Crudely, therefore, $T_g \propto [L / (r^2 a)]^{1/(4+\alpha)}$. At a given distance from the source, the smallest grains in thermal equilibrium (~ 30 Å) will be about a factor of 2 hotter than the largest grains commonly considered (~ 0.3 μm).

The heat capacity of grains with $a \lesssim 20$ Å is so low that their temperature fluctuates, being significantly affected by the absorption of a single UV photon. Grains deeper in the dusty disk will not be exposed directly to UV radiation from the central source, but to longer-wavelength re-emission from shielding gas and dust. This shielded dust will have a temperature nearly independent of a, and slightly lower (by a factor ~ $(T_{re} / 2500 \text{ K})^{1/(4+\alpha)}$) than that of the directly illuminated grains of temperature T_{re}.

The emission from dust at temperature T_g at long wavelengths scales as $\varepsilon\nu \propto \nu^{2+\alpha} T_g$, peaks very sharply at $h\nu \sim (3 + \alpha)kT_g$ ($\lambda \sim 30\, T_2^{-1}\, \mu$m, where $T_g = 100\, T_2$ K) and declines exponentially at higher frequencies. Except for the small grains of fluctuating temperature, which can contribute high frequency emission from regions where the equilibrium temperature is low, most emission at frequency v will come from the radius where the equilibrium dust temperature $T_g \sim h\nu / (3 + \alpha)\, k$, i.e., from a radius $r \propto L^{1/2} \nu^{-(4+\alpha)/2}$, and the flux of radiation at that frequency will (for an isotropic central source) be proportional to the fraction of the sky at the central source covered by dust at the appropriate radii. This radius-frequency scaling can cause curious effects. At frequencies where ν is large (e.g., $1 < \lambda < 7\, \mu$m, where $\alpha \simeq 1.7$ - Whittet 1988), the temperature is nearly independent of radius, enhancing the probability of having a large warp at an appropriate radius, and hence a large sky covering factor and a large ~ 3 μm flux (see figure 2). This may be the cause of the ``3-5 μm bumps'' commonly observed in AGN (Edelson & Malkan 1986).

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3. OUTSKIRTS OF THE GALAXY AND SUBMILLIMETER SPECTRUM

At low frequencies α is also large (α -> 2 when 0-frequency isotropic conductivity dominates the dielectric tensor), so that the temperature changes only slowly with radius at the outskirts of the galaxy (~ 3 - 30 kpc) where the molecular gas distribution of galaxies rapidly becomes very patchy. The characteristic temperature at the outskirts of a typical galaxy would be ~ 30 - 50 K (see figure 1).

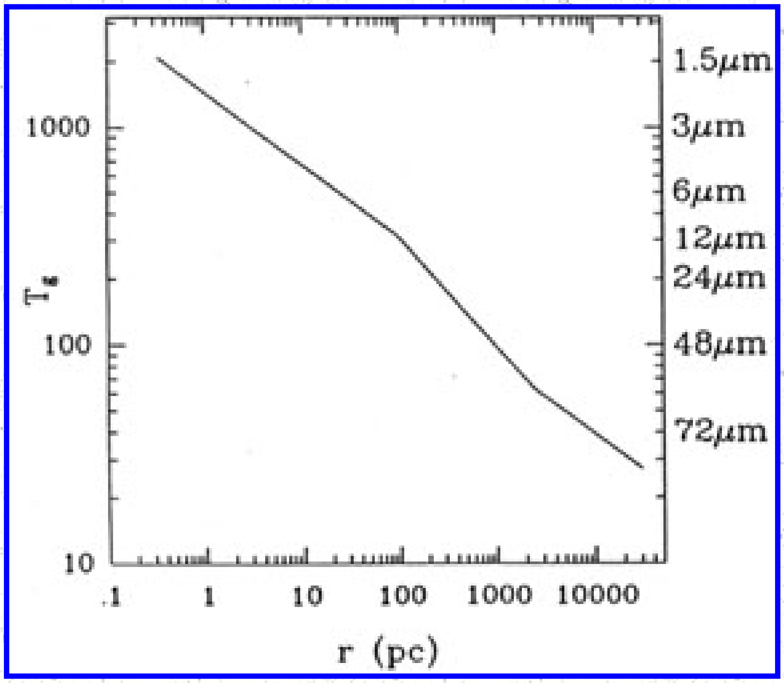

Figure 1. Temperature of directly illuminated 0.1 μm graphite grains as a function of distance from a central UV source of luminosity $L_{UV} = 10^{46}$ erg s^{-1}. Planck-averaged absorption efficiencies used are from Draine & Lee 1984. For sources of other luminosities and grains of other sizes, the temperature in the flatter portions of the curve (T > 300 K, T < 60 K) scales roughly as $(L_{UV} / a)^{1/6}$, and in the steeper portion (60 K < T < 300 K) as $(L_{UV} / a)^{1/4}$. For a galaxy disk with a smooth logarithmic warp, dust at the given temperatures contributes predominately to the flux at wavelengths marked on the right.

A dust layer wil absorb UV flux incident at an angle θ to the normal of the layer if its column density $\sigma > 10^{-2} \cos\theta$ g cm^{-2}. With a Galactic gas-to-dust ratio spread over a disk of radius r_{kpc} this column corresponds to a mass of gas $M_H \simeq 2 \times 10^8 \cos\theta\, r^2_{kpc}\, M_{\odot}$. The gas masses in nearby AGN are inferred from observations of CO (which of course depletion relates more directly to the dust than to M_H!) to be of order 10^8-10^{10} $M_\odot$ (Sanders, Scoville, & Soifer 1988a), and even in a young galaxy such as might surround a high redshift quasar it is unlikely that there would be more than ~ 10^{11} $M_\odot$ of processed gas. Consequently the disk will become optically thin beyond a few kpc (it could become thin at a smaller radius if most of the dust is clumped into clouds with $\sigma >> 10^{-2} \cos \theta$ g cm^{-2}, and such clouds at larger radii could preserve dust in neutral cores, but their covering factor would necessarily be very small).

Since the covering factor of dusty material at 20 K (~ 100 kpc) is expected to be very small, the spectrum of dust reradiation will be characterized by a rather well-defined minimum temperature, and should roll over sharply at wavelengths $\lambda \gtrsim 200$ μm with $F\nu \propto \nu^{2+\alpha}$ at longer wavelengths (as for similar reasons it is observed to do in starburst galaxies and Galactic H II regions - cf. Telesco & Harper 1980). The precise form of the spectrum at 60 μm < λ < 200 μm will vary depending on the covering factor at large radius, which could be enhanced by the presence of companion galaxies (whose starlight maintains a minimum dust temperature ~ 20 K!), tidal tails, and the like.

As we discuss in section 5, at frequencies $\nu < 10^{11}$ Hz, free-free emission from photoionized gas at the illuminated face of the disk will dominate the spectrum. Figure 2 shows the spectrum of continuum reradiation from gas and dust in an exponential disk with a logarithmic warp (d(covering factor) / $d \ln r = const$). To illustrate how material at large radii can affect the far infrared and submillimeter spectrum, we show the effect of adding reradiation from a 2 x 20 kpc slab of dust extending from 10 to 30 kpc (which could represent a companion galaxy or a tidal tail).

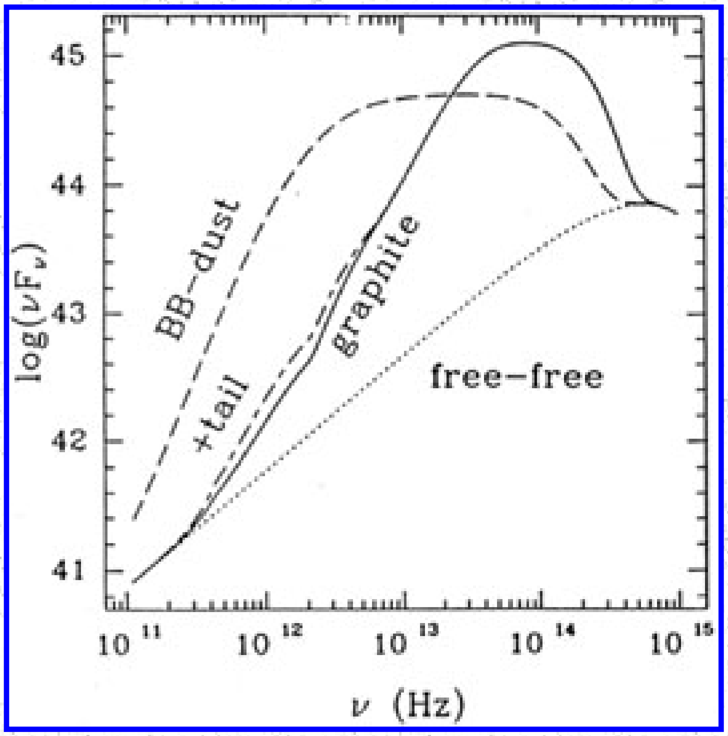

Figure 2. Spectrum of reradiation from dust and photoionized gas in a warped disk surrounding a quasar with $L_{UV} = 10^{46}$ erg s^{-1}. The solid line represents a disk containing 0.1 μm graphite dust having $C = d$(covering factor) / $dln\ r$ = 0.1 exp(-r / 10kpc). Note the ``5 μm bump." The dot-dashed line shows the result of adding 0.03 to C for 10 < r < 30 kpc - representing a tidal tail or companion galaxy. The dashed line shows the spectrum of reradiation from (very large) grains assumed to radiate as black bodies, with the same covering factor distribution as for the solid line. The dotted line shows the contribution of free-free emission from the photoionized zones above the dust. There is no freedom in its normalization relative to the dust spectra.

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4. TRANSITION DISK

Between r ~ 1 kpc and the black hole's accretion disk proper ($r \lesssim 10^3\, GM_h / c^2 \sim 0.03\, M_8$ pc for a black hole of mass $M_h = 10^8\, M_8\, M_\odot$) lies the transition disk. Unlike the accretion disk, this disk will be heated primarily by external radiation rather than by the local release of gravitational binding energy. Beyond $r \sim 20\, \sigma_2^{-2}\, M_8$ pc the stars in the galaxy, of velocity dispersion $10^2\, \sigma_2$ km s^{-1} determine the potential. A photoionized or molecular disk will be self-gravitating and Jeans unstable if its column density exceeds

$$\Sigma_{sg} \sim \Omega^2 h/G \sim 100\, T_3^{1/2} \sigma_2 r_{\rm pc}^{-1}\ {\rm g\,cm^{-3}}, \qquad (3)$$

where h is the scale height of the disk and $T = 10^3\, T_3$ K the gas temperature. If this gas flows in on a timescale t_{in} to supply the black hole with an accretion rate $\dot{M} = \dot{m}\, M_\odot$ yr^{-1}, then $\sigma \sim 1\, \dot{m}\, r_{pc}^{-1}\, v_{300}^{-1}\, (t_{in} / t_{orb})$g cm^{-2} where the orbital speed of the gas is $300\, v_{300}$ km s^{-1} and t_{orb} is the orbital time of gas at radius r. Purely local viscosity results in enormous inflow times, and Begelman, Frank and Shlosman (papers in these proceedings, and references therein) have argued that the angular momentum transport is determined by self-gravitation and global bar instabilities, so that the mean column density always exceeds σ_{sg}. Dust in such a column has an enormous optical depth to UV photons: $\tau \gtrsim 10^4\, T_3^{1/2}\, \sigma_2\, r_{pc}^{-1}$. Provided the disk is warped (by any of the mechanisms described in section 2) or flared, infrared reradiation is inevitable. A disk warped through angle θ will intercept and reradiate a fraction ~ θ / 3 of the luminosity of the central source. For idealized dust of constant α, if $C = d$(covering factor) / $d \ln r \propto r^q$, then in the `inertial range' ($kT_{min} << h\nu << kT_{max}$) the superposition of dust emission from all radii produces a reradiated spectrum with $L\nu \propto \nu^{-s}$, where

$$s = 1 + q(4 + \alpha)/2. \qquad (4)$$

Since substantial warps are to be expected on all scales, we expect in some *average* sense $q \simeq 0$ and hence $s \sim 1$. A diversity of bumps and wiggles is to be expected in individual objects, depending on the radii (and hence, via figure 1, wavelength) where their warps are most pronounced, the size and composition of their dust grains, and whether they are viewed from an angle where dust at a large radius absorbs re-emission from the interior. This seems in accord with the infrared spectral energy distributions of AGN: a great variety, with a median $s \sim 1$ (Sanders et al. 1989, 1988b). As discussed in section 2, the properties of more realistic galactic dust modify slightly the simple result of equation (4), and by flattening the $T(r)$ relation introduces a propensity for 3-5 μm ``bumps'' (see figure 2).

5. SURFACE PHYSICS AND RADIO EMISSION

It is fortunate that large column densities of material (equation 3) are expected close to the active nucleus, for there is an enormous radiation pressure on dusty gas directly exposed to a quasar's UV flux. The opacity of a single grain is $\sigma / m \simeq 2 \times 10^4 (0.1\ \mu/a)$ cm^2 g^{-1}. If the grains are coupled by collisions or Lorentz forces to gas, then with a Galactic gas to dust ratio, the total opacity is $\kappa_{gr} \simeq 200$ cm^2 g^{-1} (roughly the cross section to mass ratio of an interstellar cloud with $A_v \sim 1$). This is nearly 10^3 times larger than the Thomson opacity $\kappa_T = 0.4$ cm^2 g^{-1} which defines the Eddington limit, so radiation pressure will tend to expel unshielded dusty gas from all but the outer edges of the host galaxy. In the absence of forces other than radiation pressure and gravity, at radius r_{pc} gas in which dust survives will reach a terminal velocity

$$v_\infty \sim 10^4 L_{46}^{1/2} r_{\rm pc}^{-1/2} \kappa_2^{1/2} (1 - 0.004 L_{46}^{-1} \kappa_2^{-1} M_8 - 2 \times 10^{-4} L_{46}^{-1} \kappa_2^{-1} \sigma_2^2 r_{\rm pc})^{1/2}\ km\ s^{-1} \quad (5)$$

where $\kappa_{gr} = 10^2\ \kappa_2$ cm^2 g^{-1}. The innermost radius at which dust can survive (section 6) defines a characteristic velocity v,sub>max ~ $210^4\ L_{46}^{1/4}\ \kappa_2^{1/2}$ km s^{-1}.

The component of this radiation force normal to the disk surface, which must be balanced by vertical pressure gradients in a quasi-static situation, would destroy in a dynamical time any warp in a disk with $\sigma < 50 r_{pc}^{-1} \cos\theta$. Since this is generally less than σ_{sg} (equation 3), warps can survive. The tangential force along the disk surface cannot be balanced, so the surface layers will be ablated. The radiation force acts primarily only on a thin layer of column density $\sim \kappa_{gr}^{-1}$. Large-scale Kelvin-Helmholtz instabilities might couple the motion of that layer to underlying material, but the resulting shocks would destroy the dust in the surface layers and thus reduce the rate of ablation. With and without coupling, we find that the ablation timescale is considerably longer than the inferred inflow timescales (see section 4), so the disk is likely to survive. The fate of the dust in the surface layers is less clear. The dust can be destroyed by sputtering if it develops a high speed δv relative to the surrounding gas. Collisional coupling maintains ($\delta v)^2 \sim p_{rad} / \rho_{gas}$ (proportional to the ionization parameter) small enough near the disk that grains can survive. But since accelerated dust must pass through shocks to follow a warped surface, it may well be destroyed long before it and its associated gas reach the terminal speed (5).

The column density of a Strongren length is $\sigma_s = 0.05\ \Xi\ T_4$ g cm^{-1}, where Ξ is the ratio of ionizing radiation pressure to gas pressure, and $10^4\ T_4$ K is the temperature of the photoionized gas. Plausible transition-zone disks have $\Xi \simeq 10^{0\pm2}$ at all radii. Except in the outskirts of the galaxy $\sigma_{sg} >> \sigma_c$, so only a thin surface layer will be photoionized. If dust survives in this layer (as is especially likely in the low-density outer regions of the galaxy) resonance line emission from this layer will be converted into infrared photons, while other emission lines will be heavily reddened. If dust is destroyed (as is likely in the inner regions), the surface may contribute to (and perhaps dominate!) the emission line flux from the AGN (Collin-Souffrin 1987).

Free-free emission from the photoionized surface layers of the warped disk with electron density n_e will be optically thin at frequencies $\nu > 10^{10} (n_e / 10^5 \text{ cm}^{-3})^{1/2}$ Hz, so radio frequency free-free emission will come predominantly from the outer parts of the disk, while free-free at millimeter wavelengths could have a comparable contribution from the inner parsecs. It is easy to show that the free-free luminosity density $L\nu$ (*ff*) (the optically thin free-free emissivity, integrated over the photoionized volume), is simply related to the infrared luminosity re-radiated by the underlying (and/or cospatial, if dust survives in the photoionized surface) gas:

$$L_\nu(ff) = L_{IR}/[2 \times 10^{15} Hz \cdot (5/g(\nu, T))], \qquad (6)$$

where $g(\nu, T)$ is the Gaunt factor. The resulting free-free luminosities are comparable to those of the flat-spectrum components observed in quasars by Antonucci and Barvainis (1988), and also to the level of the radio detections in most PG quasars (Kellermanm reported in Sanders et al. 1989).

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6. SUBLIMATION AND THE TEMPERATURE GAP

The rate of sublimation of a dust grain at temperature T is given (in g cm^{-2} s^{-1}) by

$$Q = \sum_i (p_{si}(T) - p_i) S_i(T) \sqrt{\frac{m_i}{2\pi kT}}, \qquad (7)$$

where the index i runs over all equilibrium gas-phase species (e.g. C, C_2, CO, etc. for graphite grains), p_i is the partial pressure of species i, $S_i(T) \sim 1$ is the sticking fraction for molecules colliding with the grain surface, and p_{si} is the saturation vapor pressure for species i. The saturation vapor pressure is given by

$$p_{si} = \zeta_i(T) kT \frac{(2\pi m_i kT)^{3/2}}{h^3} \exp\left[-\frac{h_0}{kT} - \Delta\right], \qquad (8)$$

where ζ_i is the product of the rotational, vibrational, and electronic partition functions for the gas-phase species i, and h_0 is the heat of sublimation at zero temperature, on a per atom basis. $\delta(T)$ is a complicated expression involving integrals of the specific heat of the solid (Reif 1965, p. 367). Graphite (h_0 / k = 8.58 x 10^4 K to C, h_0 / k = 9.82 x 10^4 K to C_2, h_0 / k = 9.45 x 10^4 K to C_3, Kelley 1973) is the most refractory substance (with the exception of Tungsten!); silicate grains have $h_0 / k \simeq 6.6 \times 10^4$ K. We have fitted the thermodynamic data and sublimation measurements of graphite in vacuum (Kelley 1973), and find that the saturation vapor pressure of the dominant gas-phase constituent is well fitted by

$$p_s = 6 \times 10^{15} \exp[-92200/T] \text{ dyn cm}^{-2}. \qquad (9)$$

The gas pressure in an α accretion disk is

$$p = \frac{GM\dot{M}}{4\pi r^3 \alpha c_s} = 0.01 M_8 \dot{m} r_{\rm pc}^{-3} \alpha^{-1} T_3^{-1/2} \text{ dyn cm}^{-2}, \qquad (10)$$

This pressure is comparable to the pressure ~ 10^{-2} dyn cm^{-2} in broad-line clouds. Since the solar abundance of carbon, $C/H = 4 \times 10^{-4}$, the partial pressure of carbon, were it all in the gas phase, would be

$$p_C \simeq 10^{-5} M_8 \dot{m} r_{\rm pc}^{-3} \alpha^{-1} T_3^{-1/2}\ dyn\ cm^{-2}. \qquad (11)$$

At radii ~ 1 pc, grains grow at an impressive rate: a / adot ~ $5n_9$ (a / 0.1 μm) yr; in fact the temperatures and densities are quite similar to those in red-giant winds where interstellar dust is believed to form. [But here the grain and gas temperatures need not be equal: the ratio of a grain's radiative cooling luminosity to the rate at which it exchanges energy with gas via collisions is $L/H = 10 n_{11}^{-1} T_{g,3}^{5} / T_{H,3}^{3/2}$, where the grain temperature is $10^3\ T_{g,3}$ K and the gas temperature and density are $10^3\ T_{H,3}$ and $10^{11}\ n_{11}$ cm^{-3}, respectively]. However, comparing with equation (7) and equation (9), we see that when the grain temperatures T_g exceed 2000 K, graphite grains will certainly begin to sublimate rather than grow. For T_g > 2100 K, the timescale for sublimation of a 1 μm graphite grain becomes shorter than 10^3 yr, the timescale on which in could be replenished by inflow. From figure 1, we see that this temperature is reached at ~ 0.3 pc in our fiducial quasar.

When the dust sublimates, the gas loses its primary opacity and coolant. As the temperature rises above ~ 3000 K, most common molecules are destroyed, and the opacity drops precipitously by several orders of magnitude (Alexander et al. 1983). The gas in the interior of the disk is then unable to remain in thermal equilibrium at temperatures $2000 \lesssim T \lesssim 7000$ K, and must inevitably heat. Above ~ 10^4 K, the opacity rises abruptly to near its former level as hydrogen is ionized, providing the gas with a new thermal equilibrium state. Unless there is no warp (or down-scattering of radiation onto the disk from electrons or a jet), the transition disk at r < 0.3 pc is thus constrained by the heating from the central source to be optically thin, with $T \sim 10^4$ K, until $r \lesssim 0.02$ pc, when the incident flux can be carried by optically thick thermal emission, and the temperature will begin to rise above 10^4 K in the accretion disk. The absence of thermalized emission from material with temperatures $2000 \lesssim T \lesssim 7000$ K provides a natural explanation for the minimum in $\nu L \nu$ at $\nu = 10^{14.5}$ Hz (λ = 1 μm) observed in almost all quasars (Neugebauer et al. 1989). [The reader may mentally add an accretion disk spectrum to the right of figure 2]. Since in this interpretation the frequency is a universal constant, determined (up to very slowly varying logarithms) by the heats of sublimation and dissociation of dust and molecules, and by the ionization of hydrogen, the minimum in the reradiated $\nu L \nu$ will always be present, and observable unless filled in by starlight or a non-thermal contribution to the spectrum.

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7. CONCLUSIONS

Figure 3 summarizes our description of reradiation from gas and dust in the host galaxy of a quasar. Provided quasars are located in galaxies like those of their lower luminosity cousins, it is hard to imagine how thermal reradiation can fail to make a significant contribution to the infrared luminosity of quasars. As we have outlined above, assuming that this *dominates* provides attractively natural explanations for the shape of the far infrared and submillimeter spectrum, for the high-frequency radio emission, for the ``3 - 5 μm" bump, and for the universal minimum in νL_ν at $\nu = 10^{14.5}$ Hz. Some support for the latter can be adduced from the elegant observations of near-infrared variability in Fairall 9 by Clavel et al. (1989). The general absence of variability at longer infrared wavelengths (Neugebauer et al. 1989) is at least consistent with a thermal interpretation. Still, objections can be raised: e.g., the general absence of emission features associated with polycyclic aromatic hydrocarbons and silicates (Moorwood 1989). Nonthermal models can be contrived (and the author must confess to some involvement!) to explain many of the same features, though perhaps less naturally.

This debate will ultimately be resolved by a measurement of the brightness temperatures. Nonthermal models of the submillimeter spectrum (de Kool & Begelman 1989) require brightness temperatures $T_B > 10^{10}$ K, while thermal models require $T_B < 10^3$ K. The two models thus predict angular sizes for the emitting region differing by a factor $\gtrsim 10^4$. A submillimeter interferometer with a few kilometers baseline would determine the nature of the emission. Continued monitoring of infrared variability will also discriminate between thermal and non-thermal models (though one should beware of sources like 3C273, where a weak Blazar component seems occasionally to wobble into the line of sight). The model outlined above predicts hysteresis in the near infrared flux: when the central source increases in brightness, the near infrared flux can rise with it (with only a mean light-travel time delay). But the rise will sublimate the dust in a larger area than before, and if the central luminosity subsequently falls faster than grains can reform and grow, the dust-free ``hole" will produce a large dip in the near infrared νL_ν, at the frequencies corresponding to the missing temperatures. If the emitting dust grains are aligned by shear or a globally anisotropic magnetic field, their thermal radiation could be significantly polarized.

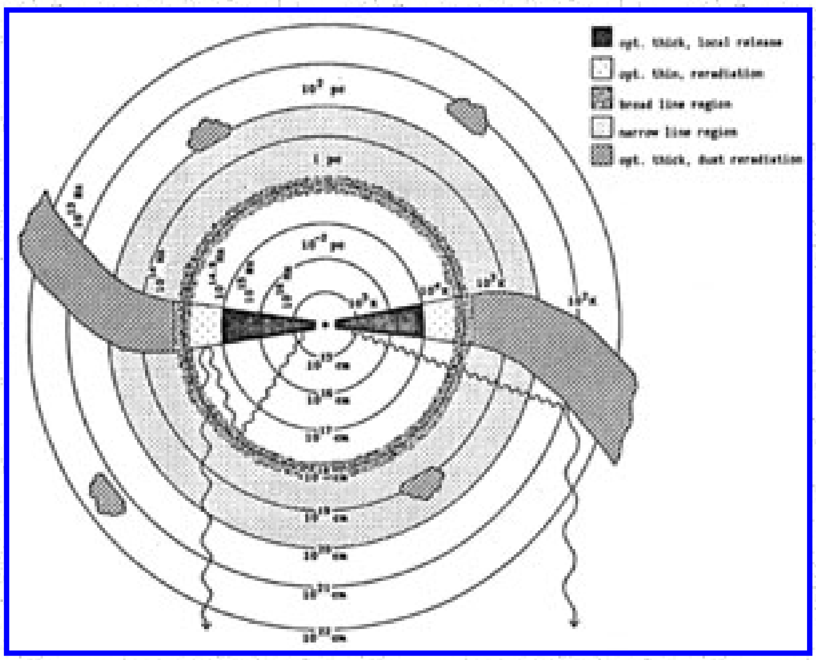

Figure 3. Cartoon illustrating the state of and frequencies of reradiation from gas in a quasar's host galaxy. Note the sudden transition in the gas temperature at ~ 10^{18} cm caused by the drop in opacity when dust sublimates.

It is devoutly to be hoped that we will soon be freed from our embarrassing ignorance (after 20 years of observations and theoretical activity) of whether the infrared emission from quasars arises from a source 10^{14} cm across, or from one 10^{22} cm across.

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