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RADIATIVE EXCITATION OF MOLECULES NEAR POWERFUL COMPACT RADIO SOURCES

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ABSTRACT

In a recent paper, Barvainis & Antonucci searched for and failed to detect CO $J = 1$–0 absorption from the obscuring torus in the nearby powerful radio galaxy Cygnus A. We show that a plausible explanation for the lack of absorption (assuming that the ionization parameter within the torus is low enough for the gas to be molecular) is that radiative excitation of the CO molecules by the nonthermal radio continuum inreases the excitation temperature of the lower rotational levels substantially, reducing the optical depths. The excitation temperature may approach the brightness temperature of the radio source at high enough flux-to-density ratios. Heating of the gas by the nonthermal excitation may also be important. We discuss the region of parameter space in which this excitation mechanism will be important and the implications for observations of obscuring tori.

Subject headings: galaxies: active — galaxies: individual (Cygnus A) — galaxies: ISM — molecular processes — radio continuum: galaxies

1. INTRODUCTION

In the unified scheme for active galactic nuclei (AGNs), it is assumed that all AGNs are intrinsically similar, having both broad- and narrow-line regions, but that in the Type 2 objects (Seyfert 2 and narrow-line radio galaxies), our view of the broad-line region and the central continuum source is blocked by a significant column density of obscuring material (see Antonucci 1993 for a review). This obscuring material is generally assumed to be in an approximately parsec-scale "torus" of molecular gas (e.g., Krolik & Begelman 1988; Krolik & Lepp 1989). Although there is indirect evidence for the existence of these tori, little or no direct information on their physical state presently exists.

If these obscuring tori are in fact molecular, then the carbon monoxide molecule should be present with a substantial abundance (Krolik & Lepp 1989; Maloney, Hollenbach, & Tielens 1994). Although the low-lying rotational transitions of CO are the most commonly observed emission lines from molecular gas, the small angular scale inferred for the tori makes observation of the CO in emission extremely difficult. However, it may be possible to observe the CO in absorption if there is a centrally located radio source. In a recent paper, Barvainis & Antonucci (1994) searched for such absorption (in the CO $J = 1$–0 line) from the powerful narrow-line radio galaxy Cygnus A. X-ray and near-infrared observations indicate that there is an obscuring column density $N_{\rm obs} \gtrsim 10^{23}$ cm^{-2} along our line of sight to the nuclear continuum source (Arnaud et al. 1987; Ward et al. 1991). *Ginga* observations give a best-fit value for the obscuring column density of $N_{\rm obs} = 3 \times 10^{23}$ cm^{-2} (Koyama 1992). In addition, Cygnus A shows luminous vibrationally excited molecular hydrogen emission within $r \sim 2h_{100}^{-1}$ kpc of the nucleus (Ward et al. 1991). Barvainis & Antonucci failed to detect any absorption ($\tau_{\rm CO} < 0.6$ for a line width $\Delta V \approx 6$ km s^{-1}). If the torus is made up of numerous small clouds, with a covering factor of only ~ 1 along the line of sight, the lack of absorption can be understood if the individual clouds are smaller than the ratio continuum source, so that at any given velocity the absorption is not very deep. (The covering factor must be at least one to produce the near-IR and X-ray obscuration.) However, this requires that there be little molecular gas in the torus which is not clumped into clouds (Barvainis & Antonucci 1994). Assuming that the obscuring gas actually is in a torus around the nucleus, there are three other possible explanations for the lack of CO absorption toward Cygnus A:

1. The torus is not molecular; X-ray ionization and heating keeps the gas of the torus atomic.
2. Part or all of the torus gas is molecular, but heating by the X-rays keeps the gas warm enough (several hundred to ~ 2000 K) that the fractional CO column density in $J = 0$ is undetectably small.
3. The CO column density through the torus is large enough for detection even at torus temperatures, but radiative pumping by the strong millimeter and submillimeter continuum of Cygnus A increases the excitation temperature of the lower rotational levels substantially above the kinetic temperature, reducing the absorption optical depths by a significant factor. This explanation was also proposed by Barvainis & Antonucci, following a suggestion by M. J. Rees (private communication).

In this paper we concentrate on the third possibility, although we will briefly discuss the other two explanations in § 2. As we show in § 3, radiative excitation by the nonthermal radio continuum is a plausible explanation for the lack of CO

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absorption from the obscuring material in Cygnus A, if the latter is in fact concentrated in an approximately parsec-scale torus. In § 4 we estimate the region of parameter space (radio flux, gas density, ionization parameter) in which the gas will be molecular and radiative excitation by the radio continuum will be important. Radiative excitation of the rotational levels may also be an important heat source for the gas; this is discussed in § 5. Finally, in § 6 we summarize our results and discuss their implications.

2. MOLECULAR ABUNDANCES AND DETECTABLE COLUMN DENSITIES

Before looking at the problem of radiative pumping of CO by a nonthermal continuum source, it is necessary to make some estimates of the physical conditions obtaining in the torus gas. We also comment briefly on the detectability of CO in absorption under these conditions. A thorough discussion of the properties of X-ray irradiated gas clouds is beyond the scope of this paper; detailed results are presented in Maloney et al. (1994). Here we simply quote some relevant results. The X-ray ionization parameter is

$$\xi = \frac{L_x}{nr^2} = \frac{4\pi F_x}{n} , \tag{1}$$

where L_x is the X-ray luminosity, n is the gas density, and r is the distance of the torus from the nuclear source. At the substantial column densities inferred to be present in obscuring tori, absorption even at X-ray energies becomes significant, and so it becomes convenient to use an effective ionization parameter,

$$\xi_{\rm eff} = \xi N_{22}^{-0.9} , \tag{2}$$

where N_{22} is the total hydrogen column density between the source and the point in question in units of 10^{22} cm^{-2}. (The column density dependence arises from the integration of the attenuated X-ray flux over the X-ray absorption cross section.) The effective X-ray ionization parameter can then be written

$$\xi_{\rm eff} = 1.1 \times 10^{-2} L_{44}/(n_9 r_{\rm pc}^2 N_{22}^{0.9}) , \tag{3}$$

where $L_{44} = L_x/10^{44}$ ergs s^{-1}, $n_9 = n/10^9$ cm^{-3}, and $r_{\rm pc}$ is the distance from the X-ray source in parsecs.

Detailed calculations of the chemistry, ionization, and thermal balance show that CO will not become abundant (fractional abundance $x_{\rm CO} \sim 10^{-4}$ or higher, depending on the gas-phase carbon abundance) unless $\xi_{\rm eff} \lesssim 5 \times 10^{-3}$. At this point, the hydrogen is still dominantly atomic (molecular hydrogen fractional abundance $x_{\rm H_2} \sim 10^{-2}$ or less). The gas will not become substantially molecular, with 50% or more of hydrogen in the form of H_2, unless the effective ionization parameter is smaller by about a factor of 5, $\xi_{\rm eff} \lesssim 10^{-3}$. (These benchmark values of $\xi_{\rm eff}$ are density dependent, but this variation can be ignored for the range of densities which are allowed here.) As the hard (2–10 keV) X-ray luminosity of Cygnus A is $L_x \approx 1.3 \times 10^{44} h_{100}^{-2}$ ergs s^{-1}, a substantial fraction of the total obscuring column (i.e., $N \sim 10^{23}$ cm^{-2}) will be molecular only if $n_9 r_{\rm pc}^2 \gtrsim 2h_{100}^{-2}$; merely requiring that much of the gas-phase carbon be in CO imposes the less restrictive condition $n_9 r_{\rm pc}^2 \gtrsim 0.4h_{100}^{-2}$. Although such high densities are not at all implausible for gas in such close proximity to an AGN, it is obvious that one reasonable explanation for the lack of CO absorption is simply that the X-ray flux through the torus is sufficiently high to keep the gas atomic, rather than molecular.

Even if the torus is molecular, it is possible that the CO is not seen in absorption simply because the fractional population in $J = 0$ is too small for detection, as a result of the substantial temperatures in the torus. In terms of $\xi_{\rm eff}$, the gas heating rate from the X-rays is approximately

$$n\Gamma_x \approx 8 \times 10^{-8} n_9^2 (f_h/0.2)(C_\alpha/0.1)\xi_{\rm eff} \text{ ergs cm}^{-3} \text{ s}^{-1} \tag{4}$$

(Maloney et al. 1994), where f_h is the fraction of primary photoelectron energy which goes into gas heating and C_α is a normalization constant for the X-ray spectrum (depending on the maximum and minimum X-ray energies and the power-law index), and we have normalized to typical values. At the densities required for the gas to be molecular at approximately parsec distances from the nucleus, the dominant cooling mechanism is usually gas-grain collisional cooling, with a rate

$$n^2\Lambda_{\rm gr} \approx 2.2 \times 10^{-32} n^2 T^{1/2} \left(\frac{3 \times 10^{-8} \text{ cm}}{a_{\rm min}}\right)^{1/2} \times (T - T_{\rm gr})(1 - 0.8e^{-75/T}) \text{ ergs cm}^{-3} \text{ s}^{-1} \tag{5}$$

where T is the gas temperature, $T_{\rm gr}$ is the grain temperature, and $a_{\rm min}$ is the minimum grain radius. Near an AGN, $a_{\rm min}$ is probably at least 15 Å, due to destruction of smaller grains by X-ray heating (Voit 1991). We adopt this value, assume that $T \gg 75$ K, and ignore $T_{\rm gr}$ compared to T, so that the cooling rate (5) simplifies considerably. Equating the result to the heating rate (4), assuming typical values of f_h and C_α, and solving for T, we obtain

$$T_3 \approx 120\xi_{\rm eff}^{2/3} , \tag{6}$$

where $T_3 = T/1000$ K. Since $\xi_{\rm eff}$ must be $\lesssim 5 \times 10^{-3}$ (for high CO abundance) and $\lesssim 10^{-3}$ (for high H_2 abundance), the gas temperature is restricted to be $T_3 \lesssim 3.5$ (high CO zone) and $T_3 \lesssim 1.2$ (high H_2 zone). Thus the gas temperatures expected in the torus will be several hundred kelvins, and possibly considerably in excess of 1000 K.

At the high densities required to keep the gas molecular, we can reasonably assume that the lower rotational levels of CO will be in LTE, even at such high temperatures. In this case the rotational partition function Q is given simply by $Q = kT/hcb \equiv kT/E_0$, where B is the rotational constant ($B = 1.922$ cm^{-1} for CO) and $E_0 = 2.7655k$. The fractional population in level J is given by

$$f_J = \frac{g_J e^{-E_J/kT}}{Q} = \frac{(2J + 1)E_0 e^{-E_0 J(J+1)/kT}}{kT} , \tag{7}$$

where g_J is the statistical weight of level J. For $J = 0$, equation (7) reduces to

$$f_0 \simeq 2.77 \times 10^{-3} T_3^{-1} . \tag{8}$$

The line absorption coefficient is

$$\kappa_\nu = \frac{g_1}{g_0} f_0 x_{\rm CO} n \frac{c^2}{8\pi\nu^2} A_{10}(1 - e^{-h\nu/kT_{\rm ex}})\phi(\nu) , \tag{9}$$

where $f_0 x_{\rm CO} n$ is the number density in $J = 0$, $A_{10} = 7.167 \times 10^{-8}$ s^{-1} is the Einstein A coefficient for the J = 1–0 transition, $\phi(\nu)$ is the line profile function, and $T_{\rm ex}$ is the excitation temperature, which for two levels with rotational quantum numbers J and J' is defined by

$$\frac{n_J}{n_{J'}} = \frac{g_J}{g_{J'}} e^{-\Delta E/kT_{\rm ex}} , \tag{10}$$

where $\Delta E = h\nu$ is the energy difference of the levels. With $\nu = 115.271$ GHz for the $J = 1$–0 line and taking $\phi(\nu_0) \approx 1/\Delta\nu$, where $\Delta\nu$ is the line full width at half-maximum (FWHM), the absorption coefficient (at the line center frequency ν_0) becomes

$$\kappa_\nu \approx 1.5 \times 10^{-15} n_0 \Delta v_5^{-1}(1 - e^{-h\nu/kT_{ex}}) \approx 8.3 \times 10^{-18} n_0/(T_3 \Delta v_5) , \quad (11)$$

where Δv_5 is the FWHM $\Delta v/1$ km s^{-1} and $n_0 = f_0 x_{CO} n$. Using equation (8) for f_0 we can write the line-center optical depth as

$$\tau_{\nu 0} \approx 0.23\left(\frac{N_{obs}}{10^{23}}\right)\frac{\langle x_{CO}\rangle}{10^{-4}}(T_3^2 \Delta v_5)^{-1} , \quad (12)$$

where $\langle x_{CO}\rangle$ is the fractional abundance of CO averaged over the total column N_{obs} through the torus. If the gas density in the torus is sufficiently high that a substantial fraction of the total $N_{obs} \sim 3 \times 10^{23}$ cm^{-2} column toward Cygnus A is molecular, then $\langle x_{CO}\rangle$ might be as high as a few times 10^{-4}, and so the line center optical depth could be considerably in excess of unity, especially if T_3 is less than 1. This conclusion is sensitive to the gas velocity dispersion; while $\Delta v_5 \sim 1$ is expected for thermal motions at $T_3 \sim 1$, substantial radial turbulence would decrease the line opacity considerably. Even in the absence of turbulence, however, equation (12) shows that a fairly substantial column density of CO could remain undetected due to the high gas kinetic temperature.

It is clear that for the Cygnus A torus, at least, the first two possibilities mentioned above to explain the lack of CO $J = 1$–0 absorption are quite plausible. In the following section we discuss the third, perhaps more interesting explanation, the effect of the nonthermal continuum on the rotational level populations.

3. RADIATIVE EXCITATION BY THE NONTHERMAL RADIO CONTINUUM

The compact central radio source in Cygnus A has a flux density at 101.43 GHz of 1.1 Jy, and a somewhat uncertain spectral index $\alpha \approx 0.1$ in the millimeter; the central source may have brightened between 1981 and 1990 (Wright & Sault 1993). With a measured redshift of $z = 0.0565$, the luminosity distance of Cygnus A ($q_0 = 1/2$, $h_{100} = H_0/100$ km s^{-1} Mpc^{-1}) is $D_L = 172 h_{100}^{-2}$ Mpc, so this observed flux density corresponds to

$$F_\nu \approx 3 \times 10^{-7}(\nu/\nu_0)^{-\alpha} r_{pc}^{-2} h_{100}^{-2} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} , \quad (13)$$

where $\nu_0 \approx 115$ GHz and r_{pc} is the distance to the radio source in pc. It is convenient to define the millimeter luminosity to be $L_{mm} \equiv [4\pi D_L^2 \nu F_\nu]_{\nu=115\,GHz} \approx 4 \times 10^{42} L_{42.6}$ ergs s^{-1}. For a radio source size $r_s \lesssim 1$ pc, the brightness temperature of the radio source is $T_b \gtrsim 2 \times 10^7$ K. If this radio continuum emission were to dominate the CO excitation, the excitation temperature of the CO rotational levels would try to approach $T_b \gg T$.

To determine under what conditions the radiative pumping of the rotational levels will dominate the CO excitation, we need to compare the radiative and collisional rates. The radiative transition rate for the rotational transition $J - 1 \rightarrow J$ is $\bar{\mathscr{J}} B_{J-1,J}$ where $\bar{\mathscr{J}}$ is the mean intensity at the line frequency averaged over the line profile. Ignoring the variation in $\mathscr{J}_\nu$ over the line profile, $\bar{\mathscr{J}} \approx \mathscr{J}_\nu \approx F_\nu/\Delta\Omega$, where the solid angle factor $\Delta\Omega = 4\pi$ for a source size $r_s \ll r_{pc}$, and $\Delta\Omega = 2\pi$ for $r_s \approx r_{pc}$. Assume that $J \gg 1$, and adopt the scalings

$$A_{J,J-1} \approx A_0 J^3 , \quad (14a)$$

$$E_J \approx E_0 J^2 \quad (14b)$$

(McKee et al. 1982) for the Einstein A-coefficients and energy levels, where, for CO, $A_0 = 1.118 \times 10^{-7}$ s^{-1}. These expressions slowly overestimate $A_{J,J-1}$ and E_J with increasing J: the error in $A_{J,J-1}$ is about a factor of 2 at $J \approx 60$ and the error in E_J is $\sim$15% at $J = 200$. We also have that $\Delta E_J \approx 2E_0 J$ (for $J \rightarrow J - 1$), so that $\nu_{J,J-1} \approx 1.15 \times 10^{11} J$. The radiative excitation rate then becomes

$$\bar{\mathscr{J}} B_{J-1,J} \approx 0.25 L_{42.6} r_{pc}^{-2}(\nu/\nu_0)^{-\alpha} \Delta\Omega_{2\pi} \text{ s}^{-1} , \quad (15)$$

where $\Delta\Omega_{2\pi} = \Delta\Omega/2\pi$. Note that equation (15) is independent of J (assuming $g_J/g_{J-1} \approx 1$) except for the ν-dependence of $\bar{\mathscr{J}}$.

To estimate the collisional rate coefficients, we have expanded the $J \rightarrow 0$ rate coefficients calculated by McKee et al. (1982) using the "infinite order sudden" approximation (Goldflam, Green, & Kouri 1977) to obtain the individual rate coefficients for transition $J \rightarrow J'$ ($J > J'$). (Using the more recent rate coefficients of Schinke et al. 1985 would make no significant difference; cf. Viscuso & Chernoff 1988). For $J' = J - 1$, we obtain (for $J \gtrsim$ a few)

$$\gamma_{JJ'} \approx 10^{-10} T_3^{0.3} \text{ s}^{-1} , \quad (16)$$

essentially independent of J. Note that equation (16) is the downward rate coefficient; the upward rate coefficient is given by $\gamma_{J'J} = \gamma_{JJ'}[(2J + 1)/(2J' + 1)]e^{-\Delta E_J/kT}$. The effective collision rate in or out of a level will be somewhat larger than this, by a factor of a few, due to collisions with $\Delta J > 1$, as these may have rate coefficients comparable to $\Delta J = 1$ collisions. To make allowance for this, we will multiply the above collision rate coefficient by a factor $\beta \sim$ 3–4.

The J level for which the radiative and collisional excitation rates are equal is then given by $\bar{\mathscr{J}} B_{J-1,J} = n\gamma_{J-1,J}$. Setting $\nu/\nu_0 \approx J$ and substituting equations (15) and (16) for the transition rates gives the expression

$$\frac{(2J + 1)}{(2J - 1)} J^\alpha e^{-5.5 \times 10^{-3} J/T_3} \approx \frac{(2.5/\beta)L_{42.6}}{n_9 r_{pc}^2 T_3^{0.3} \Delta\Omega_{2\pi}} . \quad (17)$$

Denote the solution of equation (17) by J_{eq}. If J_{eq} is small enough that the exponential factor on the left-hand side of equation (17) can be set to unity (i.e., $J_{eq}/T_3 \ll 180$), and assuming that $(2J + 1)/(2J - 1) \approx 1$, equation (17) has the approximate solution

$$J_{eq} \sim \left[\frac{(2.5/\beta)L_{42.6}}{n_9 r_{pc}^2 T_3^{0.3} \Delta\Omega_{2\pi}}\right]^{1/\alpha} . \quad (18)$$

Note that this expression is valid only if $J_{eq} \ll 180 T_3$, implying

$$\frac{n_9 r_{pc}^2 T_3^{0.73} \Delta\Omega_{2\pi}}{(2.5/\beta)L_{42.6}} \gg 1 , \quad (19)$$

where the numerical value assumes $\alpha = 0.1$. In fact, if the restriction (19) is much violated, then the radiative rates will dominate at all J.

To see the effect of the radiative rates on the excitation temperature of a transition, consider the steady state rate equation for a molecule with two adjacent levels, i and j ($j > i$):

$$n_i(n\gamma_{ij} + B_{ij}\bar{\mathscr{J}}) = n_j(n\gamma_{ji} + A_{ji} + B_{ji}\bar{\mathscr{J}}) . \quad (20)$$

(As noted after eq. [16], the collision rate coefficients used here should really be the effective rate coefficients.) Using the definition of excitation temperature (10), we can write T_{ex} for these two levels as

$$T_{ex} \approx \frac{h\nu_{ij}}{k}\left[\ln\left(\frac{g_j}{g_i}\frac{n\gamma_{ji} + A_{ji} + B_{ji}\bar{\mathscr{J}}}{n\gamma_{ij} + B_{ij}\bar{\mathscr{J}}}\right)\right]^{-1}, \quad (21)$$

where ν_{ij} is the frequency of the transition. Using the relations between upward and downward collision rate coefficients and between Einstein coefficients, and neglecting spontaneous radiative transitions compared to the stimulated and collisional rates, we can rewrite equation (21) as

$$T_{ex} \approx \frac{h\nu_{ij}}{k}\left[\ln\left(\frac{e^{h\nu_{ij}/kT} + \Upsilon}{1 + \Upsilon}\right)\right]^{-1} \quad (22)$$

where Υ is the ratio of radiative to collisional excitation rates. For $h\nu_{ij}/kT \ll 1$, the logarithmic term in equation (22) simplifies to $(h\nu_{ij}/kT)/(1 + \Upsilon)$, and so the expression (22) for T_{ex} becomes

$$T_{ex} \approx T(1 + \Upsilon) . \quad (23)$$

By definition, the radiative and collisional rates are equal at $J = J_{eq}$, and so the excitation temperature will be approximately twice the kinetic temperature. For $J < J_{eq}$, the ratio of radiative to collisional rates will be larger by approximately $(J_{eq}/J)^\alpha$, and so the excitation temperature will scale as $T_{ex} \approx 2T(J_{eq}/J)^\alpha$. Thus in order for the excitation temperature to reach the brightness temperature of the nonthermal radiation, the radiative rates must exceed the collisional rates by a factor of $\sim T_b/T$; this factor will be a function of J, since T_b is frequency dependent for a nonthermal source.

In the absence of the nonthermal radiation, the rotational levels will be populated up to some maximum J-level. In general, the rotational levels will be in LTE up to some J which is given by the solution of $n\gamma_{ji} = A_{ji}$. If $h\nu_{ij}/kT \gg 1$ for this J-level, J_{LTE}, then the maximum J which will have a substantial population is given approximately by the condition $h\nu \approx kT$. At the high densities and temperatures of interest here, collisions will dominate over spontaneous radiative transitions for all rotational levels which have any significant population in LTE, so we can adopt the latter criterion for the maximum J-level. In the absence of any other source of radiation, the excitation temperature of the levels above this $J_{max}(T)$ will approach the microwave background temperature. How much the level populations are affected by the nonthermal radiation depends on the value of J_{eq} and the variation of T_b with J. For $J \gg J_{eq}$, collisions will dominate and the rotational levels will have $T_{ex} \simeq T$. For $J < J_{eq}$, the nonthermal continuum will keep the excitation temperature $T_{ex} > T$, with the scaling discussed above for T_{ex} as a function of J. If there is no solution for J_{eq}, then the radiative rates will dominate at all J-levels.

We can estimate the effects of the nonthermal radiation on the level populations as follows. Consider first the case where the brightness temperature of the nonthermal source at 115 GHz is not too large, i.e., not much larger than the present lower limit $T_b \gtrsim 2 \times 10^7$ K. Since T_b is a function of J, there will be some J-level for which T_b has dropped to the kinetic temperature, T; denote this as J_T. In addition, there will be some J-level above which $T_b < h\nu/k$; denote this by $J_{max}(T_b)$. If $J_{eq} < J_T$ and $J_T \lesssim J_{max}(T)$, then the nonthermal excitation will not have much effect on the overall level populations, so the partition function will be essentially unaltered from the thermal case. If $J_{eq} \gg J_{max}(T)$ and $J_{max}(T_b) \gg J_{max}(T)$ (or if there is no solution for J_{eq}), then the maximum J-level which has a significant population may be much larger than $J_{max}(T)$, and so the populations of the lower states may be substantially reduced from the thermal case due to the increase in the partition function. In this case, if $J_{max}(T_b) \gtrsim 200$, i.e., there is significant population in J-levels where the rotational energy is comparable to the dissociation energy, then the molecules may be rotationally dissociated (predissociation by rotation: Herzberg 1950). Even at these large J-values, mixing of the rotational and vibrational states is probably not significant: the large ΔJ inhibits radiative transitions, while the selection rule $\Delta J = 0$ severely restricts nonradiative transitions (Herzberg 1950).

If T_b at 115 GHz is sufficiently high, then there will be either no J-level at which the brightness temperature drops to the kinetic temperature, or else $J_T \gg J_{max}(T)$, and $J_{max}(T_b)$ may be very large. In this situation, $J_{max}(T_b)$ must be $\gg J_{max}(T)$, and so if $J_{eq} \gg J_{max}(T)$, then the effects on the level populations will be similar to the second case discussed above: much higher J-levels will be populated than in the thermal case, and rotational dissociation may become important.

Radiative excitation can thus, in principle, make the CO undetectable in absorption in two distinct ways:

1. If J_{eq} is large, or if there is no finite solution for J_{eq}, the excitation temperatures of the low-J levels may be substantially increased above the gas kinetic temperature. This increase in the excitation temperature decreases the line optical depths due to the increase in the correction for stimulated emission: when $h\nu/kT_{ex} \ll 1$, the absorption coefficient $\kappa_\nu \propto T_{ex}^{-1}$. If the flux-to-density ratio is high enough ($\sim T_b/T$), then the excitation temperatures will be driven to the brightness temperature of the nonthermal source, making the CO undetectable in absorption regardless of the line optical depth. This latter condition probably does not occur in practice.
2. If the maximum J-level populated by the nonthermal excitation is much larger than would be populated solely by collisions, then the partition function may be increased by a significant factor, thereby reducing the optical depths of the lower-J lines. If T_b is large enough at high J, i.e., $J_{max}(T_b) \gtrsim 200$, the molecules may be rotationally dissociated.

We have assumed that the radio continuum continues with constant slope into the submillimeter/far-infrared region of the spectrum. It is also possible to have the lower levels excited to $T_{ex} \gg T$ at higher fluxes, without affecting the higher J levels, if the radio continuum cuts off sharply in the submillimeter/far-infrared. Qualitatively this will be similar to the case where the collisional and radiative rates are equal at some finite J_{eq}, but T_{ex} for the lower levels can be larger.

If the nonthermal radiation field continues shortward of 4.6 μm, radiative pumping of the vibrational levels may occur. Adopting an oscillator strength of $f_{01} = 10^{-5}$ for the $v = 1$–0 transitions, the radiative excitation rate into $v = 1$ can be written as

$$\mathscr{J}B_{01} = \mathscr{J}\frac{4\pi}{h\nu}\frac{\pi e^2}{m_e c}f_{01}$$
$$\approx 0.4\frac{L_{42.6}}{\Delta\Omega_{2\pi}}\left(\frac{\nu}{\nu_0}\right)^{-\alpha} r_{pc}^{-2}\ \mathrm{s}^{-1} , \quad (24)$$

where $\nu/\nu_0 \approx 565$. This rate is comparable to the radiative excitation rates for the $v = 0$ pure rotational transitions (eq. [15]). However, it is much smaller than the Einstein A-coefficients for

$v = 1$–0, which are of the order of 30 s^{-1}, unless the gas is at much less than a 1 pc distance. The effects of radiative pumping on the vibrational levels will be significant only if the radiative absorption rate is larger than the spontaneous radiative rate, and the brightness temperature of the radiation field is comparable to or greater than the energy level spacing of the vibrational levels, e.g., 3000 K for the $v = 1$ level. This requires that the brightness temperature at 115 GHz is $T_b \sim 10^9$–10^{10} K for a spectral slope $\alpha = 0.1$–0.5.

Since ΔJ changes by at most 1 in a vibration-rotation transition, radiative excitation of the vibrational levels will not have much effect on the rotational populations in $v = 0$. The only way that excitation of the vibrational levels will influence our results is if it leads to a significant reduction in the fraction of the molecules in $v = 0$, which will reduce the optical depths of the pure rotation lines. As noted above, this requires both a high excitation rate and a substantial brightness temperature of the nonthermal continuum at near-infrared wavelengths.

There is one caveat to our estimate of the importance of the nonthermal radiation: the free-free opacity due to the inner part of the torus may be large. The free-free optical depth may be written

$$\tau_v^{\rm ff} \approx 4.9 \times 10^{-2} J^{-2.1} T_4^{-1.35} \left(\frac{x_e}{10^{-2}}\right)^2 n_9 N_{23} , \qquad (25)$$

where T_4 is the electron temperature $T_e/10^4$ K and x_e is the ionization fraction. If there is a highly ionized ($x_e \sim 1$) inner edge to the torus of sufficient column density, this opacity may be significant for the lower J levels. However, the fact that we observe the central continuum source at $\nu \sim 100$ GHz implies that this is not a problem for Cygnus A, unless the radio source is more extended than the torus or the covering factor is small.

4. PARAMETER SPACE FOR RADIATIVE EXCITATION OF CO

In discussing the radiative excitation of CO, it is convenient to define the parameter

$$\Theta \equiv \frac{n_9 r_{\rm pc}^2 T_3^{0.3} \Delta\Omega_{2\pi}}{(2.5/\beta) L_{42.6}} = 4.7 \times 10^{-2} \frac{L_{44}^x \Delta\Omega_{2\pi}}{(2.5/\beta) L_{42.6}^{\rm mm} \xi_{\rm eff}^{0.8} N_{22}^{0.9}} \qquad (26)$$

where we have used equations (3) and (6) and added superscripts to distinguish the X-ray and millimeter luminosities; the quantity $(2.5/\beta)$ will be of order unity. (At fixed $\xi_{\rm eff}$ and r, Θ gets smaller with increasing column density because the required gas density decreases.) We then have that $J_{\rm eq} = \Theta^{-1/\alpha} = \Theta^{-10}$ for $\alpha = 0.1$. Because of this steep dependence, the importance of radiative excitation varies rapidly with Θ. If $\Theta \gtrsim 1$, then collisions dominate; if $\Theta < 1$, then radiative excitation starts to become important for the lower J levels, while if $\Theta \ll 1$, then the nonthermal continuum dominates the excitation at all J.

The physical conditions for which the torus gas will be mostly molecular, or at least most of the gas-phase carbon will be in CO, are restricted by the effective ionization parameter, as discussed in § 2. The "mostly molecular, CO radiatively excited (at some or all J)" regime is demarcated by $\xi_{\rm eff} \lesssim 10^{-3}$, $\Theta < 1$. For $\xi_{\rm eff} \lesssim 10^{-3}$, $\Theta \gtrsim 1$ the gas is mostly molecular and radiative excitation of the CO is unimportant. For $\xi_{\rm eff} = 10^{-3}$ and $N_{22} = 30$, equation (26) is

$$\Theta = \frac{0.6 L_{44}^x \Delta\Omega_{2\pi}}{(2.5/\beta) L_{42.6}^{\rm mm}} \simeq \frac{2 \times 10^{-2} L_x \Delta\Omega_{2\pi}}{(2.5/\beta) L_{\rm mm}} \qquad (27)$$

which shows that, for the Cygnus A torus, radiative excitation of the CO is plausibly important.

5. GAS HEATING DUE TO RADIATIVE EXCITATION

By keeping the lower rotational levels at an excitation temperature which is much larger than the gas kinetic temperature, radiative pumping of the rotational levels by the nonthermal radio continuum acts as a heat source for the gas. Here we show that this source of heating may be significant.

Every collisional excitation from level J' to level J removes energy ΔE_J from the gas, while every collisional deexcitation returns the same amount of energy. The net heating (or cooling) rate is then determined by the difference between the rates of collisional excitations and deexcitations. The number of excitations (cm^{-3} s^{-1}) is just $n\gamma_{J'J} n_{J'}$, while the number of deexcitations is $n\gamma_{JJ'} n_J$. The heating rate is then

$$\begin{aligned} n\Gamma_{\rm rad} &= n\gamma_{JJ'} n_J \Delta E_J - n\gamma_{J'J} n_{J'} \Delta E_J \\ &= n\gamma_{JJ'} \Delta E_J \frac{(2J+1)}{(2J'+1)} n_{J'} \\ &\quad \times [e^{\Delta E_J/kT_{\rm ex}} - e^{\Delta E_J/kT}] \text{ ergs cm}^{-3} \text{ s}^{-1} ; \end{aligned} \qquad (28)$$

the right-hand side of equation (28) goes to zero as $T_{\rm ex} \to T$.

To get an approximate solution for the heating rate, we proceed as follows: when there is a finite solution for $J_{\rm eq}$ (or when the brightness temperature of the nonthermal source falls below T at a J-level $\lesssim$ the maximum J for which $T_{\rm ex} \approx T$ in the absence of radiative excitation), the actual values of the level populations for all levels with $E_J \lesssim kT$, and hence the partition function, will not be altered very much from the values they would have in the absence of radiative excitation, as the difference between $e^{-E_J/kT}$ and $e^{-E_J/kT_{\rm ex}}$ will be small. So we will assume that we can use our previous expressions for Q and $\gamma_{JJ'}$. As is obvious from equation (28), the heating will be dominated by the highest J-levels which have $T_{\rm ex} > T$. Assuming that the highest J-level for which this is true is $\gg 1$, we will use our earlier scaling for E_J as a function of J, $E_J \approx E_0 J^2$, but we will let $\Delta E_J \approx 2\beta E_0 J$ to allow for $\Delta J > 1$ collisions.

With these approximations, inserting numerical values, and expanding the exponentials in square brackets, equation (28) simplifies to

$$\begin{aligned} n\Gamma_{\rm rad} &\approx 8 \times 10^{-17} n_9^2 T_3^{-0.7} \left(\frac{x_{\rm CO}}{10^{-4}}\right) \\ &\quad \times (2J+1)\beta^3 J^2 e^{-2.8 \times 10^{-3} J^2/T_3} \\ &\quad \times \left(\frac{1}{T_3} - \frac{1}{T_{\rm ex,3}}\right) \text{ ergs cm}^{-3} \text{ s}^{-1} \end{aligned} \qquad (29)$$

where $T_{\rm ex,3} = T_{\rm ex}/1000$ K. Under the conditions of interest, $T_{\rm ex,3} > 2T_3$, so this last factor is $\sim T_3^{-1}$. For $J = 15$, for example, and assuming that the exponential factor in equation (29) is ~ 1, on comparing the rate (29) to the X-ray heating rate (4) we find

$$\frac{n\Gamma_{\rm rad}}{n\Gamma_x} \approx 0.3 \left(\frac{\beta}{4}\right)^3 \left(\frac{\xi_{\rm eff}}{10^{-3}}\right)^{-2.1} \left(\frac{x_{\rm CO}}{10^{-4}}\right) \text{ ergs cm}^{-3} \text{ s}^{-1} \qquad (30)$$

where we have used equation (6) for T as a function of $\xi_{\rm eff}$. Obviously, heating due to excitation by the nonthermal continuum may be important; since the heating rate is $\propto J^3$, the precise rate is sensitive to the maximum J for which T_{ex} is significantly greater than T. If the nonthermal heating rate is too large, thermal collisional dissociation of the molecules will occur, leading to a negative feedback loop where the molecular abundances will drop until a new equilibrium is reached at a higher temperature.

6. IMPLICATIONS AND DISCUSSION

As we have shown in §§ 3 and 4, there is a substantial portion of parameter space likely to be occupied by molecular tori in powerful radio galaxies in which interaction with the nonthermal continuum will dominate the excitation of the lower rotational levels of CO, possibly rendering the lower-J CO lines undetectable in absorption. This will occur if L_{mm} is sufficiently high to either dominate the excitation or dissociate the molecules. One obvious implication is that molecular tori around powerful compact radio sources will be undetectable in CO absorption experiments unless the flux-to-density ratio is low, the approximate criterion being given by equation (25): $n_9 r_{pc}^2 T_3^{0.3} \Delta\Omega_{2\pi} \gtrsim (2.5/\beta)L_{42.6}^{mm}$. Thus, if independent estimates of the obscuring column density can be made (e.g., from X-ray absorption studies) and precise measurements of the X-ray and millimeter luminosities are obtained, the presence of low-J CO absorption can constrain the minimum distance of the torus from the nuclear radio source (this distance being a function of gas density).

The most direct test of this model, comparison of CO absorption toward obscured AGNs with and without luminous radio sources, is made problematic by the difficulty of actually doing the absorption experiment for any but the brightest millimeter continuum sources. It is in principle possible, however, to at least distinguish the case where radiative excitation (but not rotational dissociation) is important from the case where the torus gas is not molecular, by looking at CO *emission* from the torus. As noted earlier, if the maximum J-level populated by the nonthermal radiation is not much larger than the maximum J which would be populated solely by collisions, the change in level populations for levels with $E_J \lesssim kT$ from the collisions-only case will not be very large. The increase in excitation temperature of the lower J-levels will, however, decrease the optical depths substantially. In the optically thin regime, the emergent intensity from the torus in a given line is just $I_\nu \approx N_u h\nu A_{ul}/4\pi$, where N_u is the column density in the upper state of the transition and A_{ul} is the Einstein A coefficient; assuming the partition function is unchanged, this is independent of T_{ex} for $E_J \ll kT$. Thus CO emission can, in principle, be detected from tori for which no absorption is detectable. Since the typical torus temperatures could be high enough that the low-J CO emission is only marginally optically thick, even in the absence of radiative excitation, the emission from tori with and without central radio sources may not be very different.

In this paper we have concentrated on the effects of the nonthermal radio continuum on CO, since, for this simple diatomic molecule, it is relatively easy to make analytic estimates of the radiative excitation and heating. However, many other molecules (with the notable exception of H_2, which has no pure rotational transitions longward of 28 μm) will also be affected by the nonthermal continuum, albeit with different scalings for J_{eq} due to the differences in A coefficients, collision rate coefficients, and the more complicated electronic and rotational structure of some species (e.g., OH and H_2O). An interesting possibility is that masing may occur in tori for which radiative excitation is important: for rotational energy levels near J_{eq}, the excitation and gas kinetic temperatures will be different, and will change fairly rapidly with J. However, detailed modeling is necessary to evaluate the likelihood of masing in these conditions.

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