Supporting the Obscuring Torus by Radiation Pressure

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The Basic Problem

N(type 2) ~ N(type 1) implies $\Delta\Omega_{obscured} \sim \Delta\Omega_{unobscured}$

which in turn implies $h_{obscured} \sim r$

but $h/r \sim \Delta v/v_{orb}$, yet $v_{orb} \sim 100$ km/s

If $\Delta v = c_s$, then $T \sim 10^5$ K >> T_{subl} (dust)

If 10^5 K is too hot, what supports the obscuring matter?

Candidate Mechanisms

- Bouncing magnetized clouds stirred by orbital shear (K. & Begelman 1988, Beckert & Duschl 2004)

  But is this degree of elasticity plausible? And their collision rate must not be >> the orbital frequency

- Warped thin disk (Sanders et al. 1989)

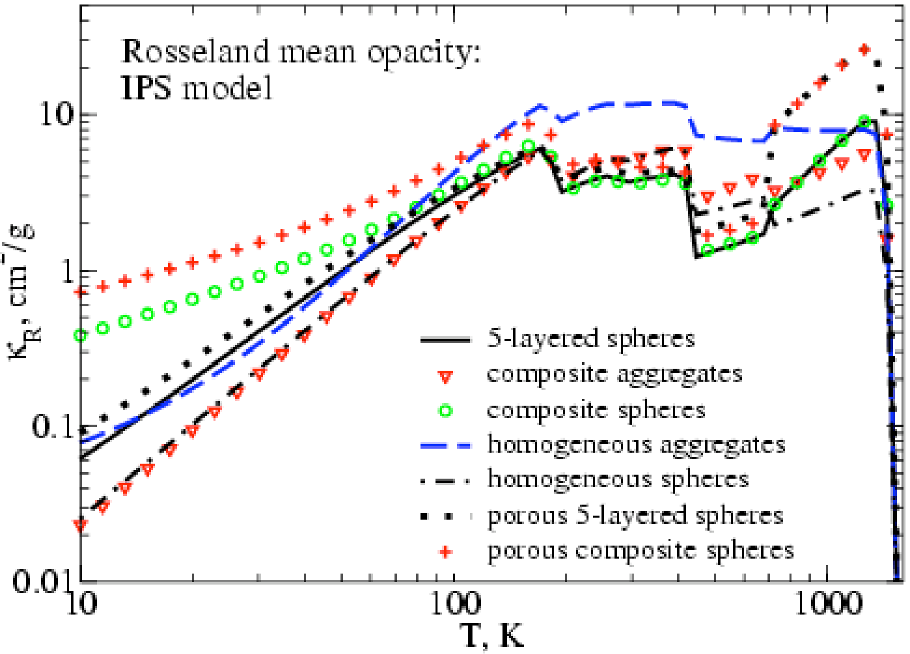
  But well-formed ionization cones are seen close to the center, and IR interferometry shows a thick structure at ~1 pc in NGC 1068

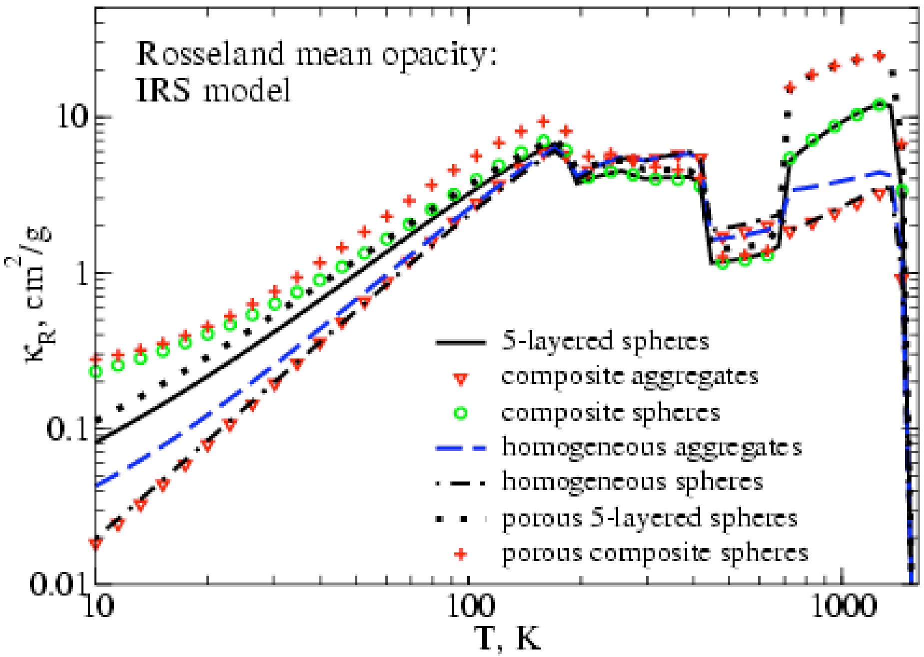
- Magnetic wind (Königl & Kartje 1994)

  But origin of large-scale field? And mass-loss rate can be very large: 10 N_{H24} (h/r)(v_{r100})r_{pc} Msun/yr

Another Candidate Mechanism: Radiation Pressure (Pier & K. 1992)

- If thermal continuum is created by dust reprocessing, there must be a large radiation flux through the obscuration
- κ_{midIR}(dust) ~ 10—30 κ_T (Semenov et al. 2003) so $(L/L_E)_{eff} \sim (10\text{–}30)L/L_E$





Radiation Transfer and Dynamics Must Be Consistent

- $\mathbf{F_{rad}}$ moves dusty gas, altering radiation transfer.
- New transfer solution changes $\mathbf{F_{rad}}$

The Simplest Self-Consistent Picture

Assumptions:

- Hydrostatic
- 2-d, axisymmetric, time-steady
- opacity independent of T, diffusion approximation (smooth density distribution)
- no sources of infrared inside the torus
- $l/l_{Kep} = j(r)$

Solution: Entirely Analytic

Step 1: Hydrostatic balance + diffusion equilibrium lead to

$r\, dj^2/dr + 2(1- \alpha)\, j^2 = 3 - 2\alpha$ for $\alpha = - d \ln \Omega / d \ln r$,

so that $j^2(r) = [j_{in}^2 + f(\alpha)](r/r_{in})^{2(\alpha-1)} - f(\alpha)$

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In other words,
If Frad,z ~ Fgrav,z in a geometrically thick disk, then
Frad,r ~ Fgrav,r likewise
So the orbiting matter must have sub-Keplerian rotation
if it is to remain in equilibrium; magnetic angular
momentum redistribution?

Step 2: Requiring both components of force balance to give a consistent density leads to

$$(\partial E/\partial z)/(z\Omega^2) - (\partial E/\partial r)/\{r\Omega^2[1-j^2(r)]\} = 0$$

which is analytically solvable by characteristics:

E = constant on (almost) elliptical surfaces

Step 3: Two boundary conditions:

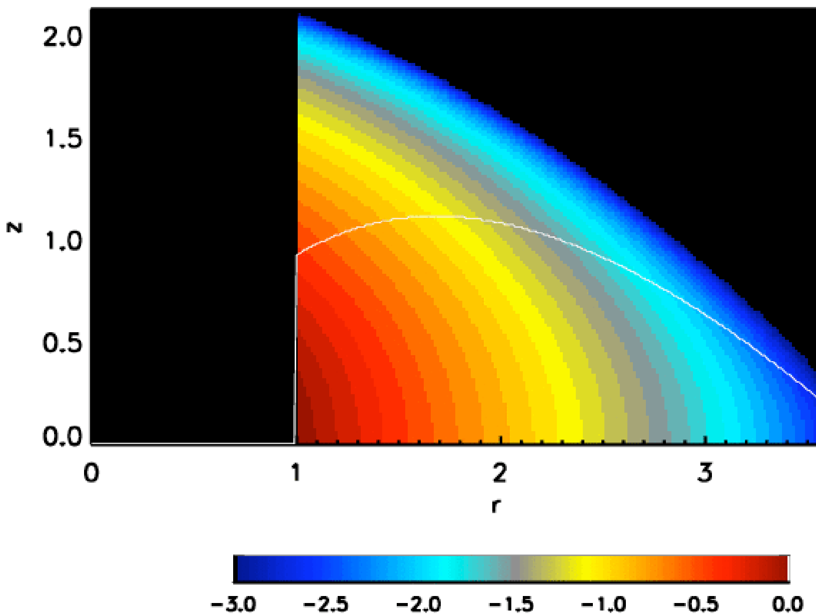
A) To fix the quantity of available matter---

$$\rho(r,z=0) = (\tau_*/\kappa r_{in})(r/r_{in})^{-\gamma}$$

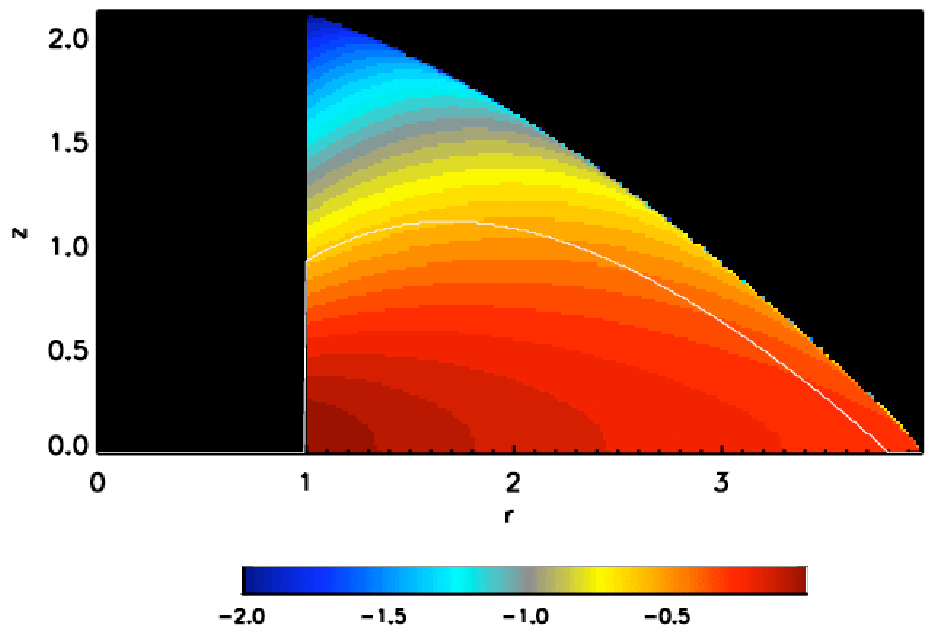
B) To match the diffusion solution to its outgoing flux---
$F \sim cE$ at the dust photosphere (which determines γ)

Example Solution

for $\alpha = 3/2$, $\tau_* = 10$, $L/L_E = 0.1$—0.3

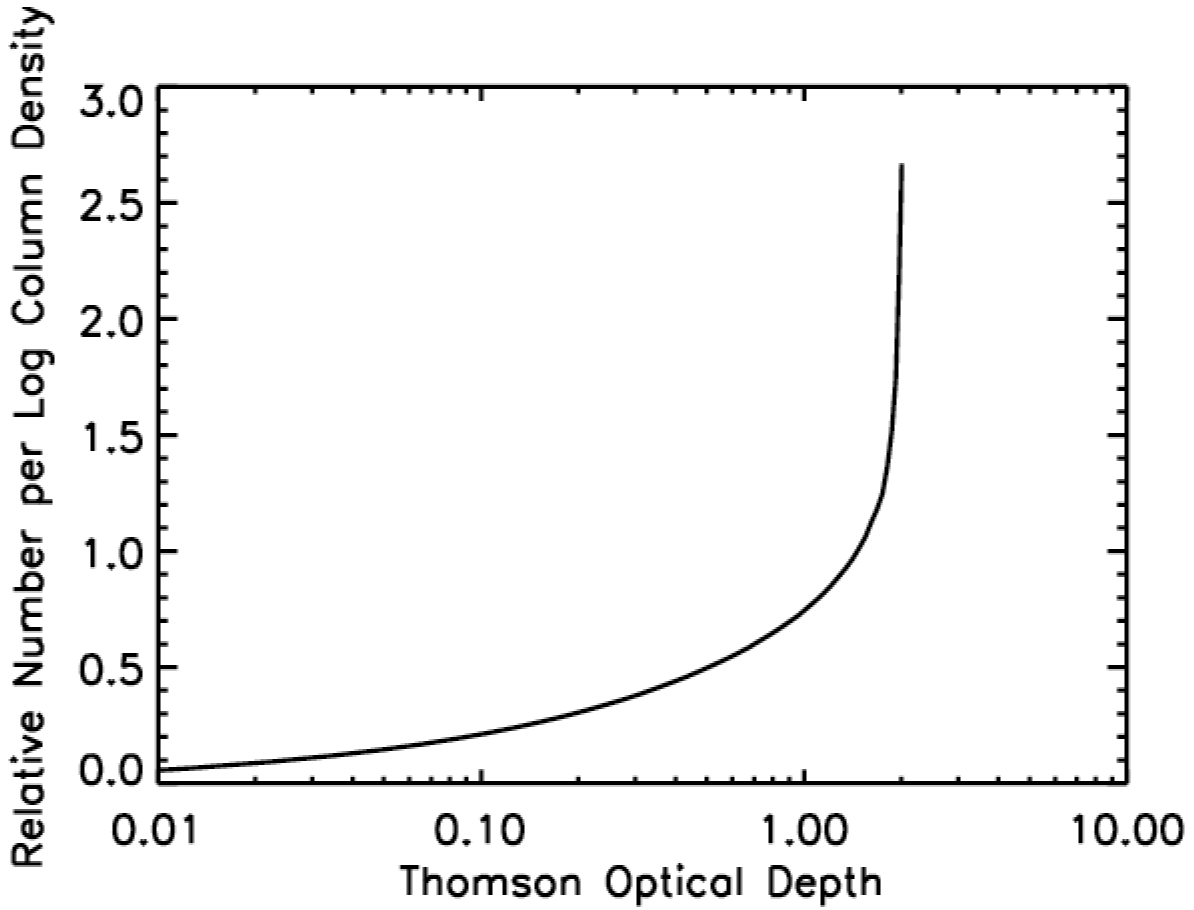


radiation energy density



gas density

The X-ray Column Density Distribution Predicted by the Example Solution



Conclusions

- Tori convert optical/UV flux to IR; there **must** therefore be a large IR flux through them
- Mid-IR opacity/mass ~ 10—30 Thomson, **increasing** the effective F/F_E by that factor
- With some simplifying assumptions, a self-consistent hydrostatic equilibrium and 2-d diffusive transfer solution can be found
- The torus becomes geometrically thick when $L/L_E \sim 0.03$—0.3 and the midplane $\tau_T \sim 1$