Dusty windshield

Radiative magnetohydrodynamics simulations of IR and UV radiation pressure on dusty AGN tori

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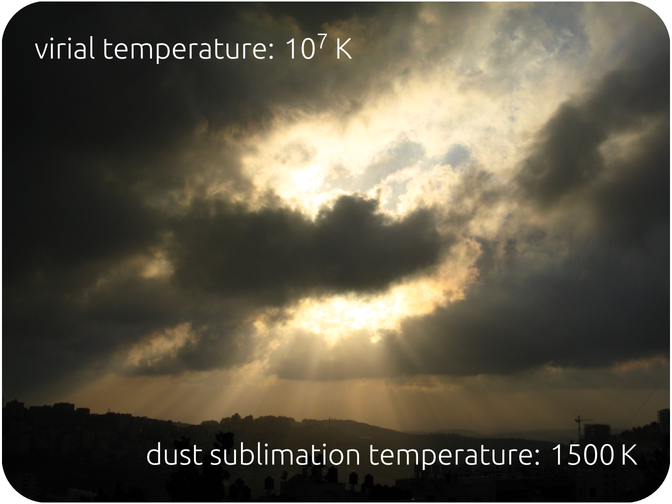
Geometrical thickness of the obscuring torus



Ramallah

Dynamical models of the obscuring torus

- Warped disk (e.g., Phinney 1989)
  blocks large solid angle only with severe warps and twists
- Clumpiness (Krolik & Begelman 1988)
  needs unusual magnetic fields to counter inelastic collisions
- Magnetocentrifugal wind (e.g., Königl & Kartje 1994)
  needs large-scale magnetic fields
- Supernovae (e.g., Wada & Norman 2002)
  needs more energy than observed
- Stellar ejecta (e.g., Schartmann et al. 2009)
  ties torus lifetime to starburst
- Radiative support (e.g., Pier & Krolik 1992)
  has not been tested with full radiative hydrodynamics (RHD)

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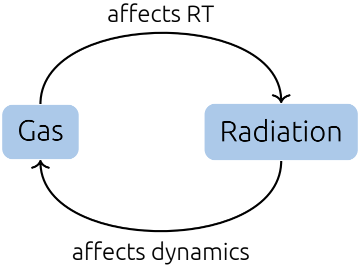
Interaction between gas and radiation



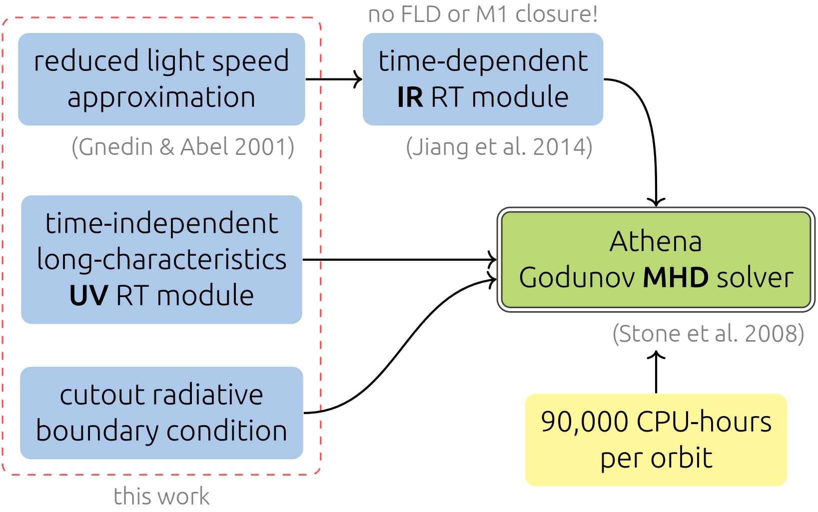
- Requires simultaneous solution of gas and radiation
- Requires quality RT near photosphere

Outline

1. Our recent radiative magnetohydrodynamics simulations
2. Lessons about torus-scale inflow and outflow

Our recent radiative magnetohydrodynamics simulations

Simulation code



no FLD or M1 closure!

reduced light speed approximation

(Gnedin & Abel 2001)

time-dependent **IR** RT module

(Jiang et al. 2014)

time-independent long-characteristics **UV** RT module

Athena Godunov **MHD** solver

(Stone et al. 2008)

cutout radiative boundary condition

90,000 CPU-hours per orbit

this work

Simulation parameters

Luminosity

0.1 times Eddington

IR opacity

20 times Thomson
if below sublimation

Optical depth

Thomson: 2
Infrared: 40

extrapolatable to realistic AGNs

Central mass

0.8 solar mass

UV opacity

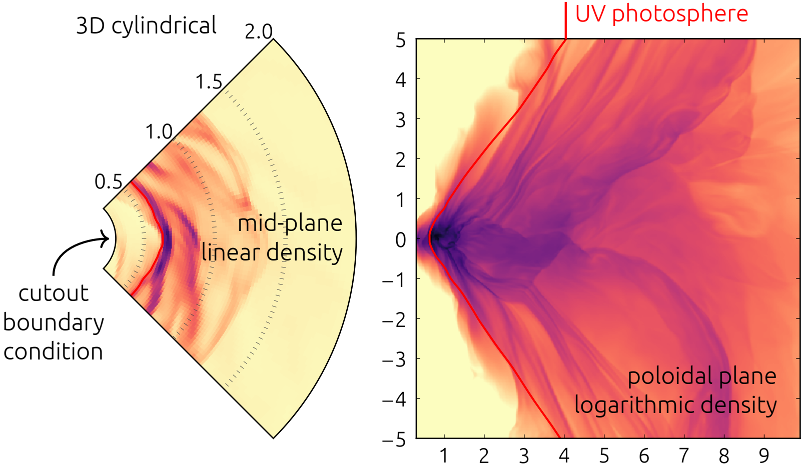
80 times Thomson
if below sublimation

Angular momentum

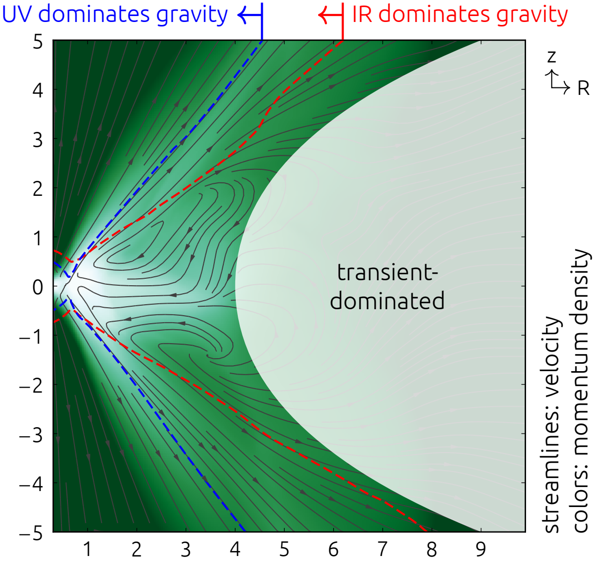
flat radial profile

genuinely arbitrary

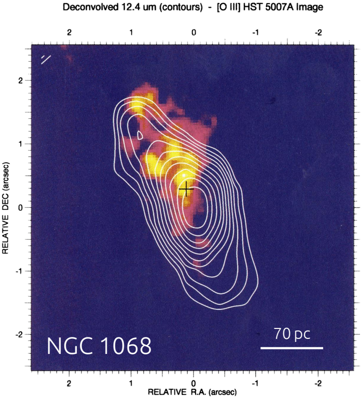
Simulation domain



Radiation-driven inflow–outflow



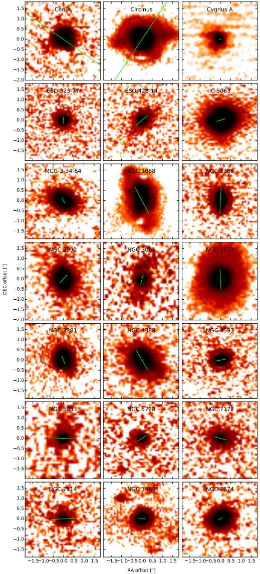
Dust in polar regions of AGNs



(Braatz et al. 1993)

colors: [O III] λ 5007
contours: 12.4 μm

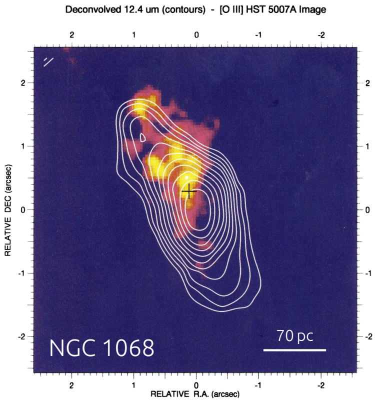
(Asmus et al. 2016)



orange: 12 μm
green: system axis (100 pc)

Dust in polar regions of AGNs

1/2



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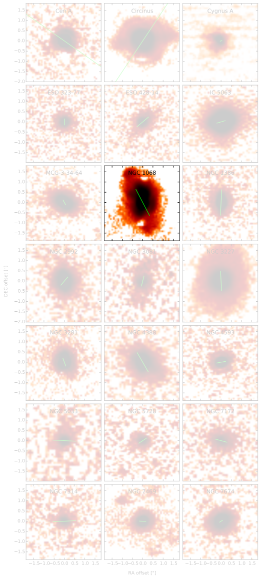

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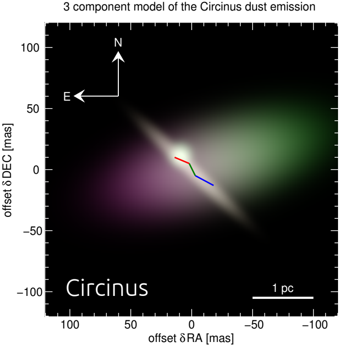
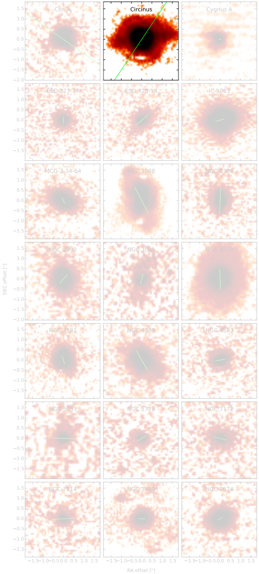


colors: dust model from VLTI
line: maser disk

(Tristram et al. 2014)

(Asmus et al. 2016)



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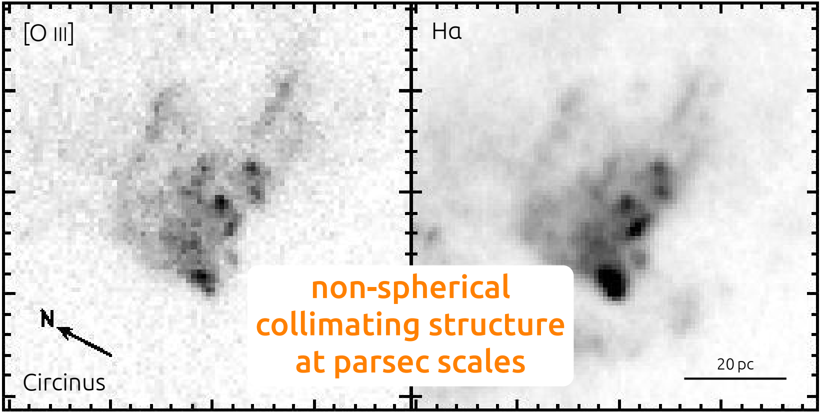
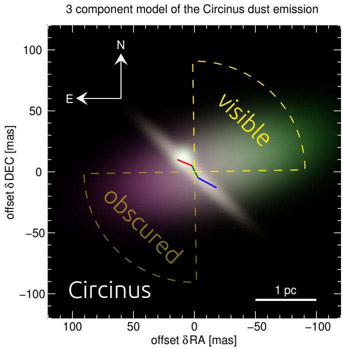


non-spherical collimating structure at parsec scales

(Wilson et al. 2000)

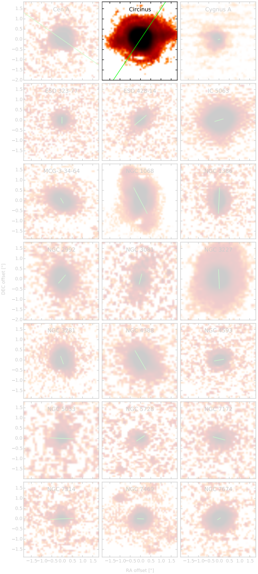
Dust in polar regions of AGNs



(Tristram et al. 2014)

colors: dust model from VLTI
line: maser disk
yellow: ionization cone

(Asmus et al. 2016)



orange: 12 µm
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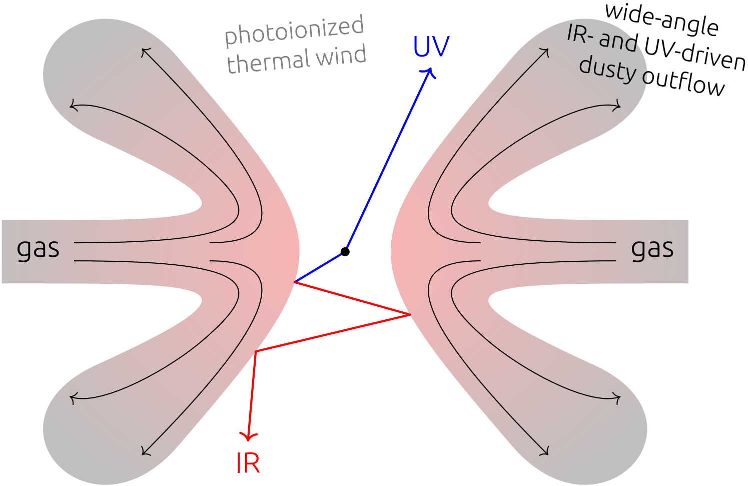
Cartoon of inflow–outflow torus model



Radiation-driven outflow

- **Kinematics** fits expectations

$$\dot{M}_{\mathrm{wind}} \sim \frac{L_{\mathrm{UV}}}{c v_\infty} \qquad \frac{L_{\mathrm{kin}}}{L_{\mathrm{UV}}} \sim \frac{v_\infty}{c} \qquad v_\infty^2 \equiv \frac{GM}{R_{\mathrm{in}}} \frac{L_{\mathrm{UV}}}{L_{\mathrm{E}}} \frac{\kappa_{\mathrm{UV}}}{\kappa_{\mathrm{T}}}$$

- **Mass loss rate** and **speed** match observed

$$\dot{M}_{\mathrm{wind}} \sim 0.2\, M_\odot\, \mathrm{yr}^{-1} \times \left(\frac{M}{10^7\, M_\odot}\right)^{3/4} \left(\frac{L_{\mathrm{UV}}/L_{\mathrm{E}}}{0.1}\right)^{3/4}$$

$$v_\infty \sim 900\, \mathrm{km\, s}^{-1} \times \left(\frac{M}{10^7\, M_\odot}\right)^{1/4} \left(\frac{L_{\mathrm{UV}}/L_{\mathrm{E}}}{0.1}\right)^{1/4}$$

temporal variation: 10 %

Radiation-driven outflow explains AGN **outflows**

Radiation-driven outflow

- **Covering fractions** are close to observed type-2 fraction

$$\begin{aligned} 0.71 &\lesssim C_{\mathrm{IR}} \lesssim 0.73 \\ 0.77 &\lesssim C_{\mathrm{UV}} \lesssim 0.82 \\ 0.78 &\lesssim C_{\mathrm{soft}} \lesssim 0.83 \\ 0.15 &\lesssim C_{\mathrm{hard}} \lesssim 0.28 \end{aligned}$$

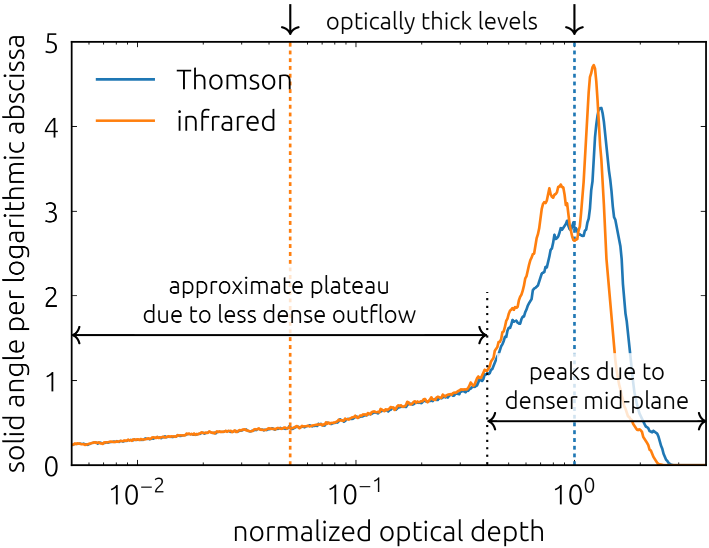
due to mid-plane and outflow;
same for all central mass

due to mid-plane;
dependent on central mass

- Flat **column density distribution** agrees with X-ray studies

Radiation-driven outflow explains AGN **obscuration**

Radiation-driven outflow



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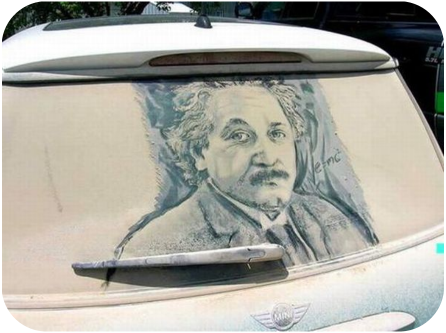
Radiation-driven outflow explains AGN **obscuration**

Spotting dusty windshields in the wild

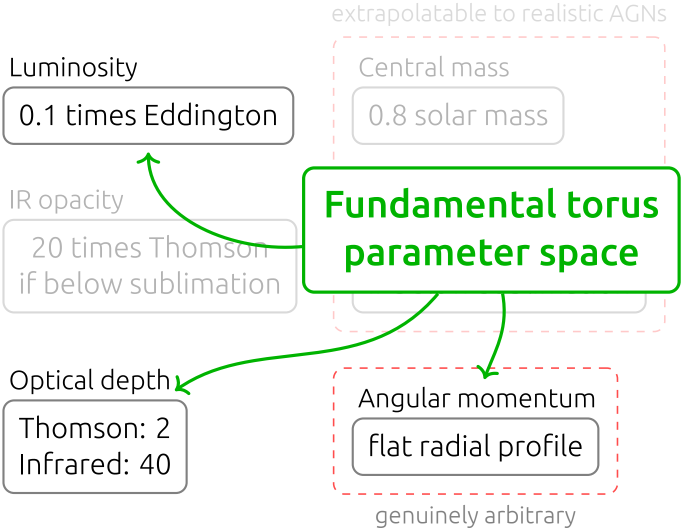
{ How can we measure the physical properties of the outflow? }

{ How can we measure the geometrical thickness of the inflow? }



Lessons about torus-scale inflow and outflow

Simulation parameters



extrapolatable to realistic AGNs

Luminosity

0.1 times Eddington

Central mass

0.8 solar mass

IR opacity

20 times Thomson
if below sublimation

Fundamental torus parameter space

Optical depth

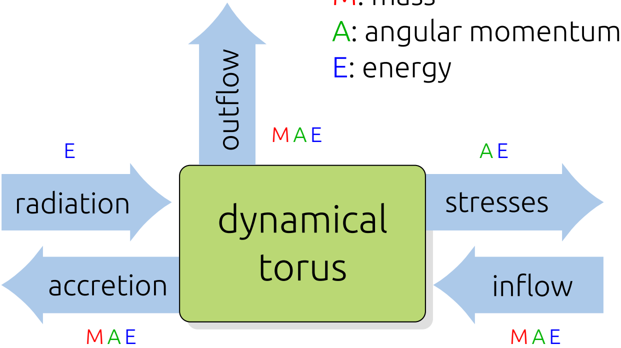
Thomson: 2
Infrared: 40

Angular momentum

flat radial profile

genuinely arbitrary

Torus as a flow-through system

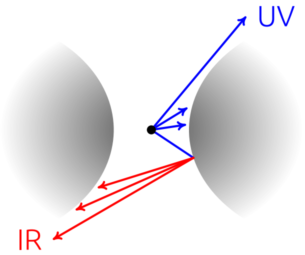


M: mass

A: angular momentum

E: energy

Constraint from mass



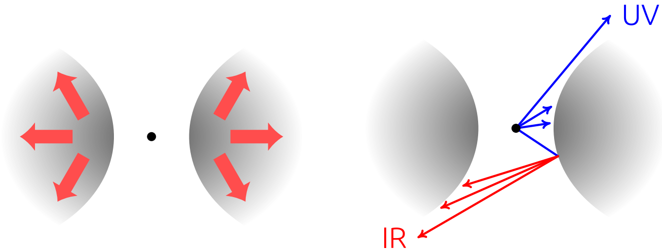
- UV and IR shave off high-latitude dusty gas
- Mass loss rate is 0.1 $M_\odot$ yr^{-1}
- But assuming $M = 10^7\,M_\odot$, $L_{\mathrm{UV}}/L_{\mathrm{E}} = 0.1$, $\tau_{\mathrm{T}} = 1$:

Mass	$\sim 2\pi r_{\mathrm{ds}}^2 \tau_{\mathrm{T}}/\kappa_{\mathrm{T}}$	$\approx 7 \times 10^3\,M_\odot$
Orbital period	$2\pi (GM/r_{\mathrm{ds}}^3)^{-1/2}$	$\approx 5 \times 10^3$ yr

Mass must be **resupplied** from galactic scales

Constraint from angular momentum

1. Isotropic pressure demands sub-Keplerian rotation
2. UV and IR provide additional radial momentum



Angular momentum must be **sub-Keplerian**

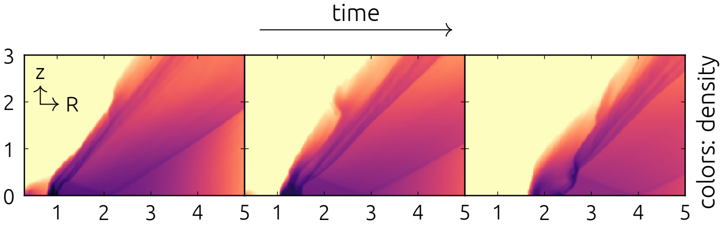
Constraint from angular momentum

3. Accretion toward inner edge requires low angular momentum
   - Inflow timescale due to stresses is $\sim [\alpha (H/R)^2 \Omega]^{-1}$
   - Inflow timescale at all radii must be comparable to outflow timescale

Angular momentum must be **low** or rapidly removed

Constraint from energy

- Radiation does positive work on outflows
- Binding energy of torus decreases
- Torus eventually becomes unbound



Energy must be kept **low**

Constraints on inflow of steady-state torus

1. Mass must be resupplied from galactic scales
2. Angular momentum must be sub-Keplerian
3. Energy must be kept low

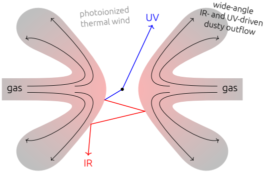
How can mass resupply satisfy constraints 2 and 3?

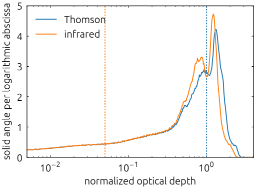
- Stresses in inflow rapidly remove angular momentum and energy
- Mass resupply has inherently low angular momentum and energy

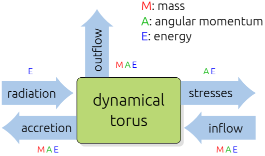
How can we measure the rotational profile of the inflow?

Summary

- Torus in RMHD simulations settles into steady inflow–outflow
- IR in central hole drives high-latitude, wide-angle outflow with expected:
  - kinematics
  - obscuration properties
- Steady-state irradiated tori must:
  - be resupplied with mass
  - have sub-Keplerian rotation






M: mass
A: angular momentum
E: energy

outflow
M A E

E
radiation

A E
stresses

dynamical torus

accretion
M A E

inflow
M A E

References I

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References II

Wilson, A. S., Shopbell, P. L., Simpson, C., et al. 2000, AJ, 120, 1325