THERMODYNAMICS OF OPTICALLY THICK DISKS

with Shigenobu Hirose and Jim Stone

Basic Disk Processes

Turbulent magnetic stresses make torques;

Differential torques cause angular momentum loss;

Angular momentum loss leads to inflow.

Torques do work;

Differential work leads to energy injected into turbulence;

Dissipation of turbulence liberates heat;

Photons are created by hot electrons;

Photons diffuse out, eventually reaching distant observers.

Thermodynamics Matters

Ultimate source for light we see, but also and more specifically,....

Determines gas equation of state, governing hydrostatic support and compressive wave propagation

Fluctuations determine lightcurve

Atmosphere structure determines departures from Planckian spectrum, both fine-scale and qualitative (e.g., coronae?)

Long-term Program Goals

A better-defined equation of state

Radiation forces

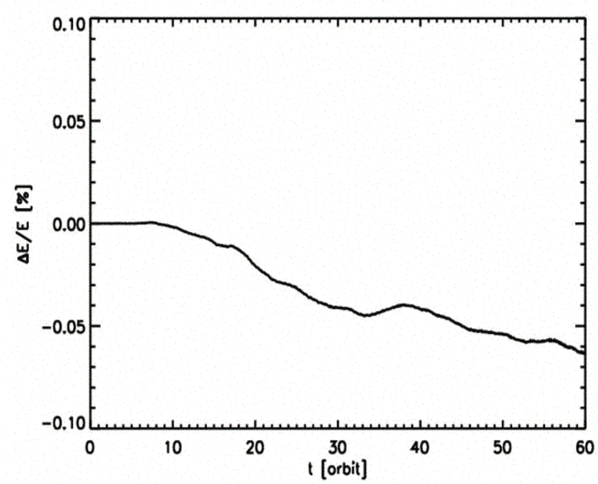
Thermal balance---is it stable?

Numerical Prerequisites

Energy conservation essential!

Basic elements:

At each time-step and in each cell, departures from energy conservation captured into gas internal energy: both electromagnetic and kinetic energies counted.



Flux-limited diffusion for radiation energy

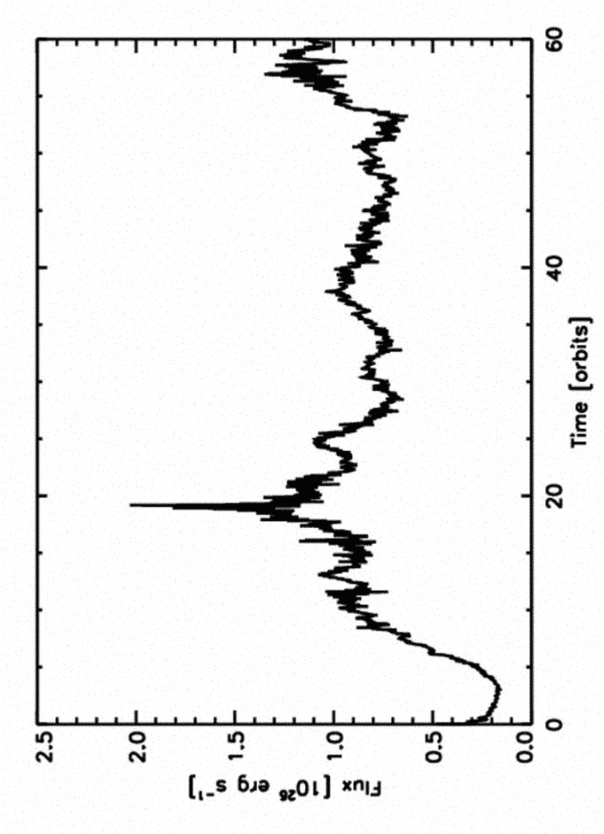
First Step: Structure of Gas Pressure-Dominated Disk

Shearing box (2H x 8H x 16H) with parameters chosen so that in the midplane $p_r \sim 0.1\ p_g$:

M = 6.6 Msolar
$r = 300\ r_g$
Surface density such that $\alpha = 0.03$ gives $L/L_E = 0.1$

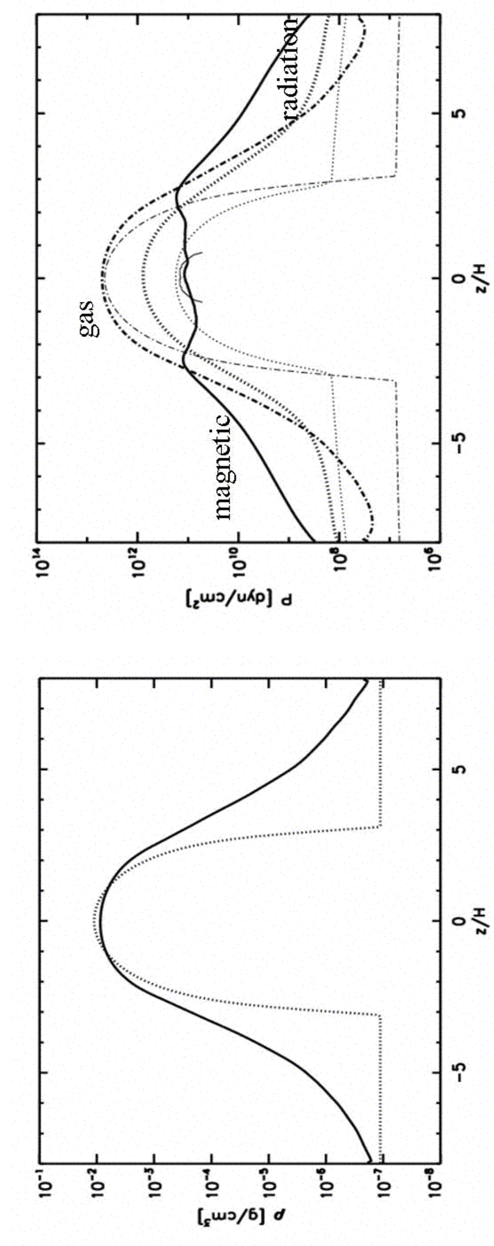
Duration = 60 orbits

Quick Relaxation to a Steady-State

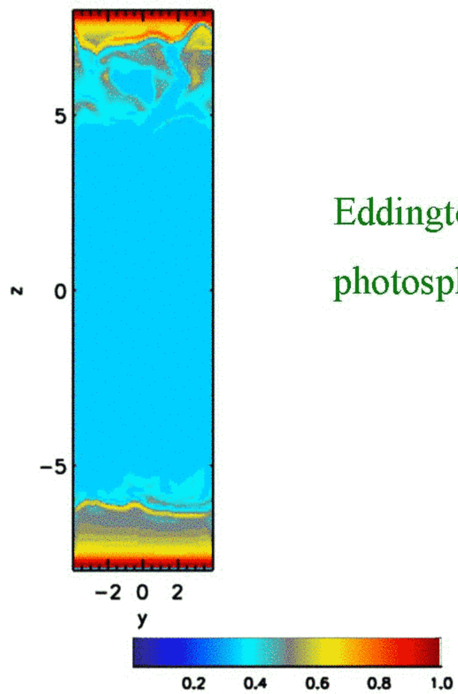


$t_{cool} = 11.4$ orbits

Mean Vertical Profiles

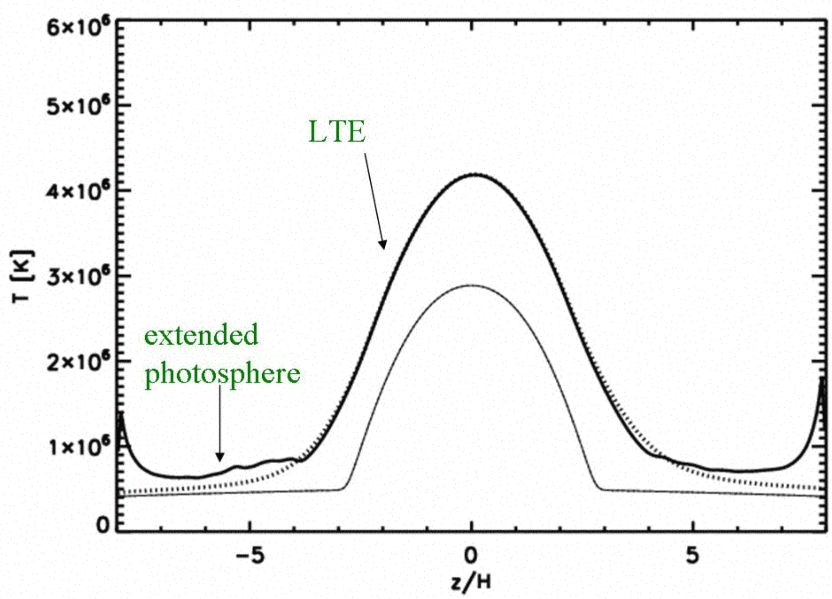


A High, Fluctuating Photosphere

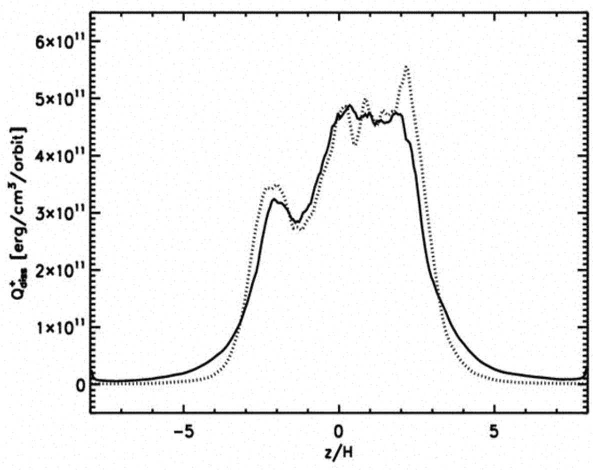


Eddington factor f;

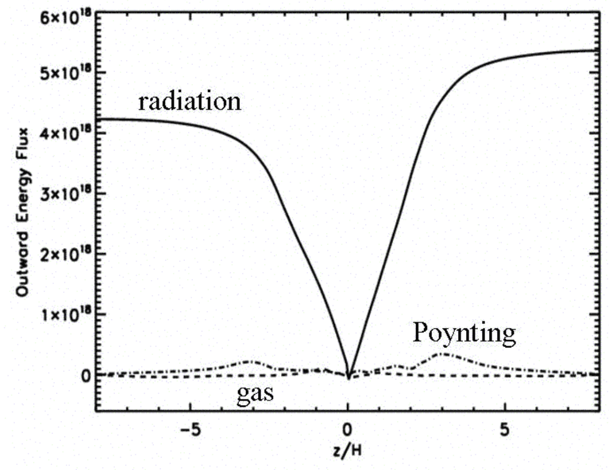
photosphere near f = 0.5



Mean Energy Flow



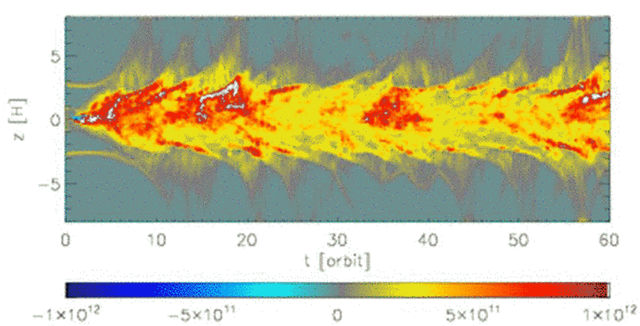
Time-average dissipation, stress



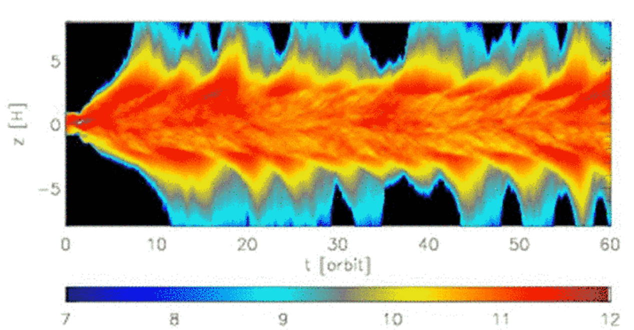
Time-average energy fluxes

Persistent Asymmetries

Horizontally-averaged dissipation (linear scale)

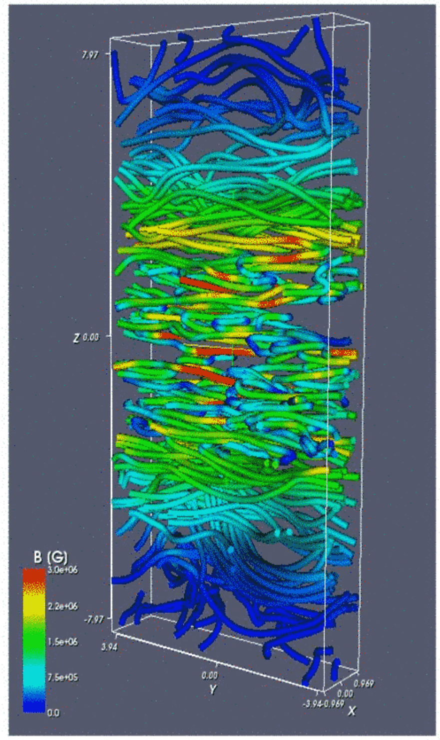


Horizontally-averaged field intensity (logarithmic scale)



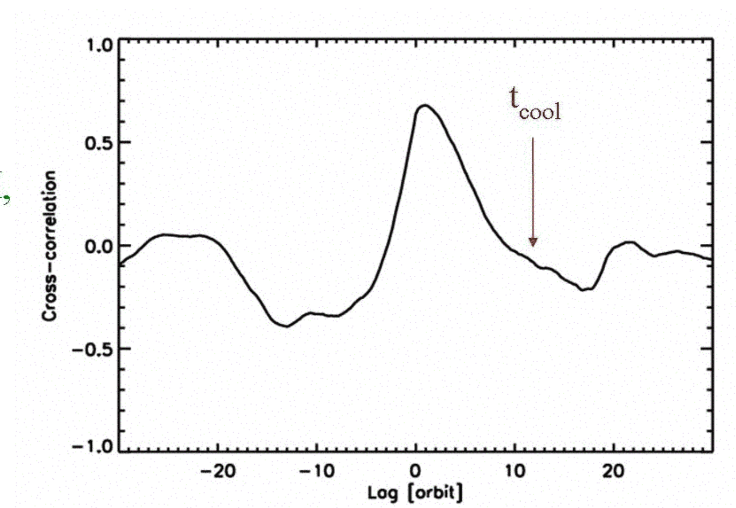
A Quiet Corona

Dissipation takes place mainly where the plasma β is relatively large, well inside the disk body.



Flux Responds Quickly to Fluctuations in Dissipation

Fluctuations in dissipation disproportionately near 2—3 H, where photon escape time is short



A Few Likely Consequences

- Extended, low-density atmosphere may lead to non-Planckian emergent spectrum
- Outgoing flux responds quickly to heating fluctuations
- Little dissipation at high altitude: where is the hard X-ray-producing corona?