RADIATION (MAGNETO)HYDRODYNAMICS PROBLEMS IN ASTROPHYSICS

Bruce Remington, panel chair

Jim Bailey, Patrick Hartigan, Bob Heeter,
Peter Hoflich, Jack Hughes, Julian Krolik

Importance of Radiation to Astrophysical Dynamics

- Radiative cooling generally determines equation of state
- Radiation fluxes often exert significant forces
- Nonlinear self-regulation of cooling and force: photoionization, optical pumping often control opacity

Photons Dominate Heat Transport

- In diffusion, outweigh electrons by ratio $(c/c_{se})(\sigma_e/\sigma_\gamma)(p_r/p_e)$
- Photons not held by magnetic fields or atomic binding
- Exchange energy with fluid, both microscopically (electron/atom absorption, scattering) and macroscopically (bulk)

Radiation Forces

- **g_r** = (κ/c)**F :** proportional to flux and opacity
- Competition generally gravity

  Ratio ~ κ L/M; in Sun, ~ 3 x 10^{-5} for $\kappa = \kappa_T$

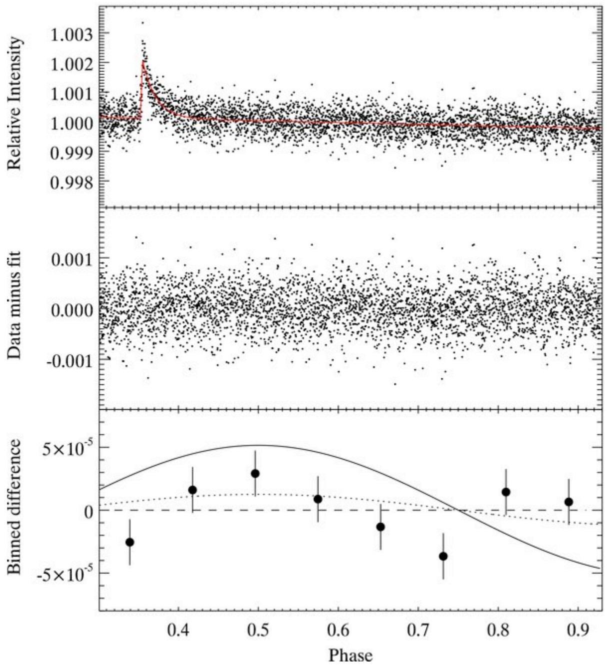
  but can easily approach or exceed 1 elsewhere

Examples of Noteworthy Problems

Exoplanet Atmospheres

- Transiting planets now permit rudimentary photometry of their atmospheres (spectroscopy in future?)
- Hydrodynamic response of atmosphere depends on differential heating by absorption of starlight, reradiation, energy flow through atmospheric latent heats:

  i.e., climate physics



GJ876d 8μ *Spitzer* data:
Seager & Deming 2009

Radiation in Star-Formation Dynamics

- Radiative cooling controls self-gravitational fragmentation
- Young stars “active”: EUV, soft X-rays–

  >Photoionization influences surrounding plasma conductivity, magnetic coupling; opacity

  >Photoionization can ablate dense gas (e.g., Eagle Nebula)

  >Heating warms nearby gas, alters dust properties
- Dust opacity to IR >> electron scattering—

enhances radiation forces

Challenge is to understand the system as a whole:

pace, mass use efficiency, stellar mass function,…

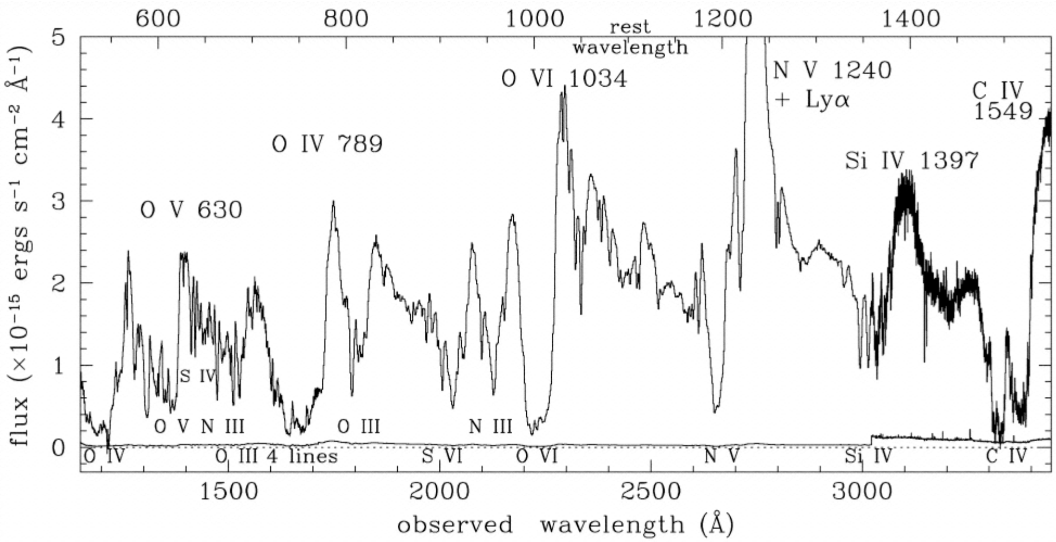
Line-Driven Winds

- Abundance of resonance lines in UV

  Large forces exerted by UV sources
- Strong UV continua in massive stars, AGN

  Powerful winds observed in both:

  $v_{stars} \sim 0.01$ c $\qquad v_{AGN} \sim 0.1c$
- But in AGN, photoionization may destroy opacity



Where is the flow?

How is it shielded?

Why ~ 0.1c?

PG0946+301: Arav et al. 2001

White Dwarf Cooling Ages

- After birth, temperature declines monotonically

  Can we use it as a stellar-population clock?

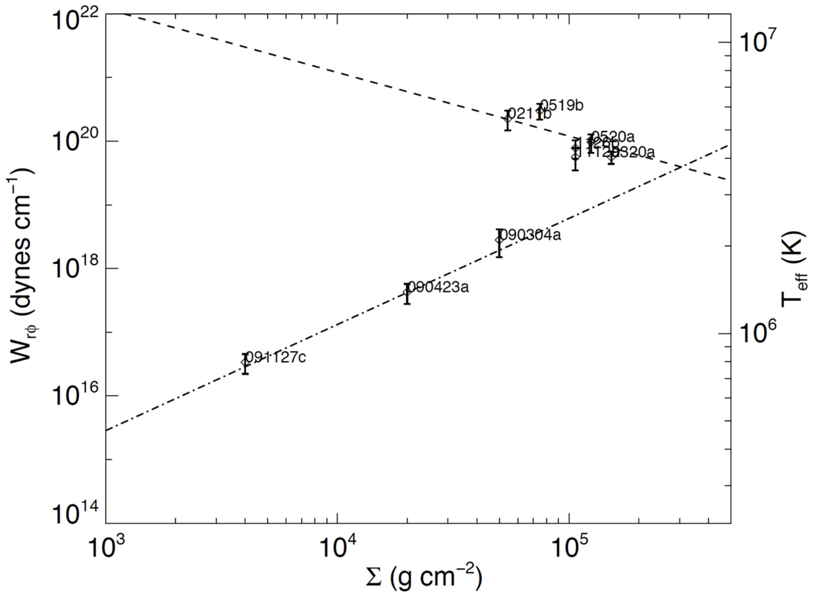
  But—
- Interior EOS
- Degeneracy effects on electron conduction
- Chemical stratification in atmospheres
- Uncertain opacities

  Collisional broadening of Lyα, H_2 , He Rayleigh-scattering affected by atomic correlations, strong magnetic fields; He free-free likewise, also atomic polarization

  Current error in greatest ages ~ 1/3 Hubble time

Radiation Forces in Black Hole Accretion

Black hole accretion: ~ 10% of the light in the Universe



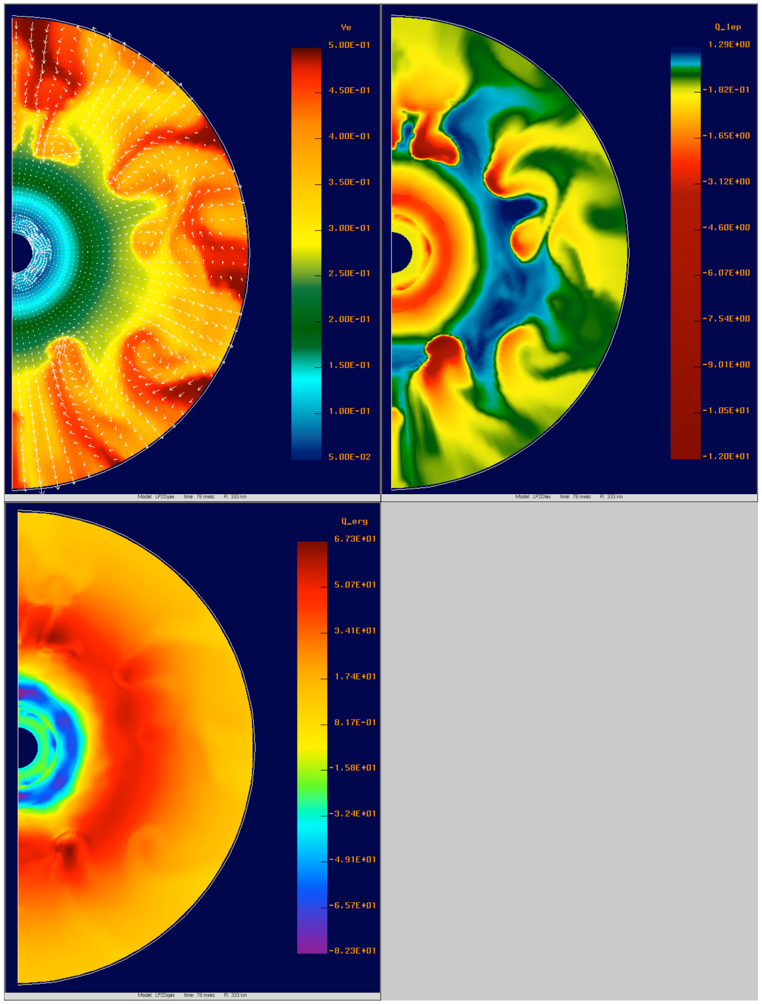
Hirose, Blaes & K. 2010

Accretion in disks; vertical support often primarily from radiation: nominally unstable to inflow fluctuations; what is genuine global behavior?

Estimated masses suggest L ~ L_E: How does distant mass source know about the limit? What happens if mass supply is larger?

Neutrino transport in collapsing stars

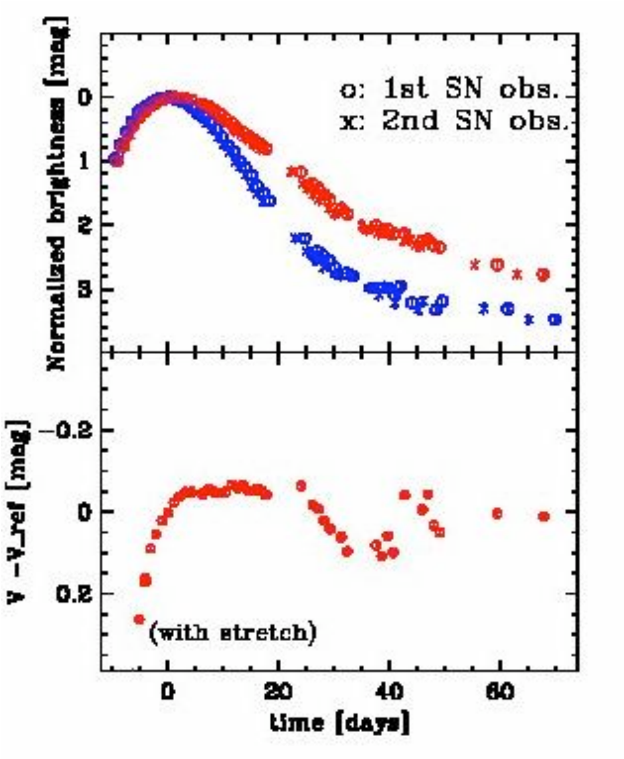
- At near-nuclear densities on ~10 s timescales, photons immobile; diffusing neutrinos carry heat, momentum
- In Type II supernovae, can neutrinos drive the explosion?
- In γ-ray burst sources, can neutrino annihilation launch the jet?



Janka & Mueller 1996

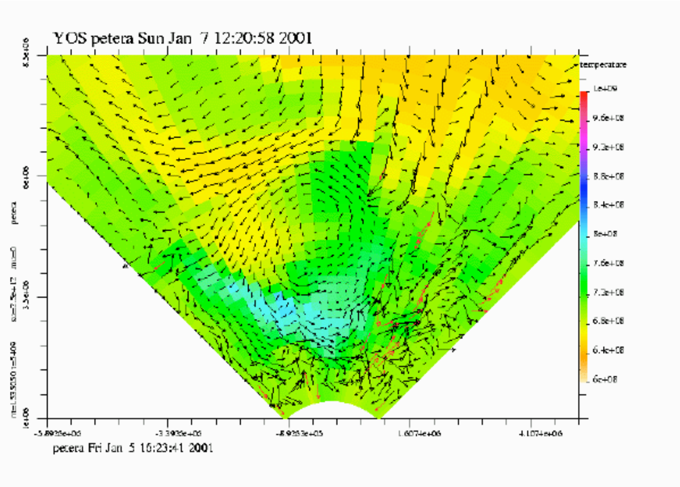
Radiation in Type Ia Supernovae

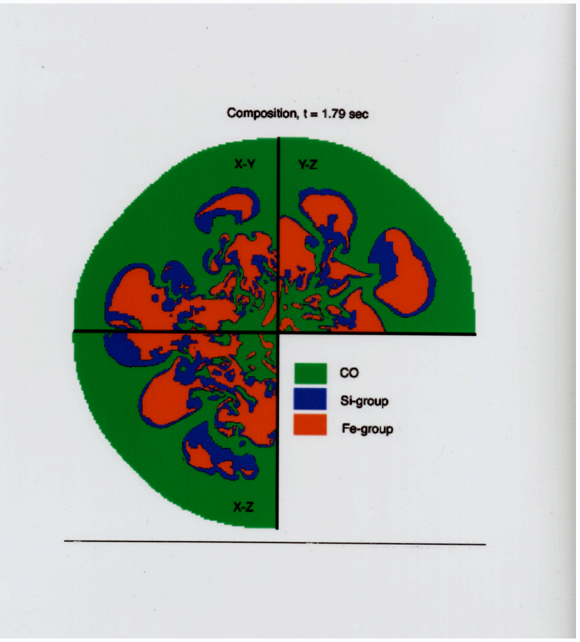
- Maximum luminosity tightly-regulated, tied to duration of bright phase; permits cosmological distance measurements, original evidence for cosmic acceleration
- If $P_{cosmic} = w\rho$, w(z) experiments seek < 2% accuracy
- Can radiation physics inform the calibration?



Type Ia Supernova Physics

- Accretion raises white dwarf mass to Chandrasekhar, igniting nuclear burning (C/O → Si/Ni)
- Radiation diffusion pre-heats ahead of burning front; influences Si/Ni output; Ni decay powers the light
- As shock encounters circumstellar matter, non-local, non-LTE energy transport influences lightcurve details





Avenues for Progress: Computational

Common Element:
Solving Transfer Along with Hydrodynamics

Continuum: Exoplanet atmospheres, star formation dynamics, black hole accretion, supernovae, neutrinos

Line: Stellar winds, BAL quasars, (white dwarf atmospheres)

Continuum-Dominated

- Energy conservation essential
- For fluid equations in conservative form, need appropriate formalism for using radiation pressure tensor (e.g. Stone & Sekora 2010)
- For “shape” of the pressure tensor (i.e., the Eddington tensor), need angular information: must solve transfer problem
- Standard tool for transfer solution flux-limited diffusion, but problematic in complex geometry: need more accurate reliable method

Line-Dominated

- Momentum conservation more important than energy conservation
- Current radiation transfer solutions based on Sobolev approximation localization, ALI (easy solutions for $\tau >> 1$, $\tau << 1$) or simplified geometry (e.g., radial rays, unique resonance locations)
- Accompanying continuum can photoionize, alter opacity (many current calculations assume pure absorption model)
- Optical pumping introduces non-local nonlinearity, greatly enlarges number of quantities to calculate ($N_{elements}$ x N_{ions} x N_{states})

  How to cope?

Long-Term Challenge:
Relativistic Radiation Hydrodynamics

Numerous additional complications:

- Special relativistic—beaming, boosting
- General relativistic—lensing

Summary

Topic vital to numerous important astrophysical contexts from exoplanets to cosmology to accreting black holes

Difficulties due to complexity, nonlinearity; progress in physical understanding algorithm-limited