Electron Heating in (Hot) Accretion Flows

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Outline

• Accretion in hot/cold disk regimes
• Hot accretion flows, e.g., Sgr A*
• Hot, dilute => collisionless
• Kinetic-MHD model for collisionless plasma
• Local shearing box sims. of collisionless MRI
  => $\alpha, q^+_e/q^+_i$
• Calculate $\eta$ (& $\dot{M}$) in 1-D models
• Conclusions & Future work
Modes of Accretion

- Thin, dense (optically thick) disk [S&S]
- local BB: $G M \dot{M}/2r \approx 4\pi r^2 \sigma T^4 (T_e = T_i)$
- high/soft state

- Low density => no cooling => hot, thick (optically thin), collisionless disk [RIAF, ADAF]
- detailed electron heating/cooling ($T_e < T_i$) for radiation
- low/hard state
Accretion Luminosity

- Standard model: \( L = \eta \dot{M} c^2 \), \( \eta \) (BH spin)
- \( \eta \approx 0.1 \) for thin disks
- For Sgr A*, \( L_{\text{obs}} \ll 0.1 \dot{M}_{\text{Bondi}} c^2 \Rightarrow \eta \ll 1 \) or/and \( \dot{M} \ll \dot{M}_{\text{Bondi}} \)? observational degeneracy
- \( \eta \) (electron heating/cooling) in RIAFs
Electron Heating

- $e^-$s lighter => radiate (from radio to X-rays)
- thin disk steady BB vs. thick disk non-BB
- $\beta<1$ corona/jet => $e^-$ acc., X-ray by IC, radio from jet
- thermal $e^-$ heating in thick disks due to MRI turbulence (this talk); well posed idealized problem
- $e^-$ acc. in corona much more difficult to understand!

[from Balbus 2003]
Sgr A*

$4 \times 10^6 \, M_\odot$ black hole

$r_{\text{Bondi}} \sim 0.1 \text{ pc (2'')}, n \sim 100 \text{ cm}^{-3}, T \sim 1.2 \text{ keV}$
[Baganoff et al. 2003]

$\dot{M}_{\text{Bondi}} \sim 10^{-5} \, M_\odot / \text{yr}$ fed by colliding massive stellar outflows

$L_{\text{obs}} \sim 10^{36} \text{ erg/s} \sim 10^{-5} \times (0.1 \dot{M}_{\text{Bondi}} c^2)$

$m_{\text{f}} (\propto T^2/n) \sim r_{\text{Bondi}} \Rightarrow$ collisionless at small $r$, where most energy is released
Drift Kinetic Equation

plasma is collisionless, hot, $H \sim r$

$\rho_{i,e} \ll H_r \ll \lambda_{mfp}$

drift kinetic equation: approx. for Vlasov eq. if $k\rho_i \ll 1$, $\omega \ll \Omega_i$, averaging over fast gyromotion $\Rightarrow$

$$\frac{\partial f_{0s}}{\partial t} + (V_E + v \hat{b}) \cdot \nabla f_{0s} + \left(-\hat{b} \cdot \frac{DV_E}{Dt} - \mu \hat{b} \cdot \nabla B + \frac{1}{m_s} (q_s E || + F_{g||}) \right) \frac{\partial f_{0s}}{\partial v ||} = 0$$

$f(x,v,||,\mu)$ in 5-D phase space!

$V_E = c(\text{EXB})/B^2$; $\mu = v_{\perp}/B \propto T_{\perp}/B$ is conserved
Kinetic-MHD

moment eqs. similar to MHD

pressure anisotropic wrt $B$

how $p_\|, p_\perp$ evolve? higher order moments $q_\|, q_\perp$

closure problem

$q \approx -nv_t^2 \nabla_\| T / (k_\| v_t + u)$  [Snyder et al. 1997]

like saturated conduction [McKee & Cowie]  
free-streaming particles carry heat

includes collisionless effects like Landau damping

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0, \\
\rho \frac{\partial \mathbf{V}}{\partial t} + \rho (\mathbf{V} \cdot \nabla) \mathbf{V} = \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi} - \nabla \cdot \mathbf{P} + \mathbf{F}_g, \\
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}), \\
\mathbf{P} = p_\perp \mathbf{I} + (p_\| - p_\perp) \mathbf{b}\mathbf{b},
\]

\[
\rho \frac{B}{D} \frac{D}{Dt} \left( \frac{p_\perp}{\rho B} \right) = -\nabla \cdot \mathbf{q}_\perp - q_\perp \nabla \cdot \mathbf{b}, \\
\rho^3 \frac{B}{B^2} \frac{D}{Dt} \left( \frac{p_\| B^2}{\rho^3} \right) = -\nabla \cdot \mathbf{q}_\| + 2q_\perp \nabla \cdot \mathbf{b},
\]

=>$ \text{as } B \uparrow, p_\perp \uparrow \& p_\| \downarrow; \Delta p \text{ natural}$
Shearing-box sims.

Local approx. w. coriolis/tidal forces. Periodic boundary conditions in $\phi, z$.
Shearing periodic in $r$.
Jump of $(3/2)\Omega L_x$ in $V_\phi$.
Sims. w. a net vertical flux!
$\Delta p$ due to MRI

\[
B \cdot \nabla B \rightarrow \left(1 - \frac{p_\parallel - p_\perp}{B^2}\right) B \cdot \nabla B
\]

pressure anisotropy ($p_\perp > p_\parallel$) as $B \uparrow$

$\mu \propto \langle v_\perp^2 \rangle / B \propto p_\perp / B = \text{const.}$

pressure anisotropy stabilize resolved MRI modes when $\Delta p$ arbitrary

How large can pressure anisotropy become? Anisotropy driven instabilities: mirror, ion cyclotron, etc.

$|\Delta p/p| \approx 0.5/\beta^{1/2}$, $\beta = 8\pi p / B^2 \sim 10-100$

Microinstabilities $\Rightarrow$ MHD like dynamics
Protons; [Kasper et al. 2003]

Pressure anisotropy reduced by Larmor-scale instabilities (not captured by DKE); thus subgrid models for instabilities:

protons: ion-cyclotron, mirror ($p_\perp > p_\parallel$)
electrons: electron-whistler ($p_\perp > p_\parallel$)
firehose for ($p_\perp < p_\parallel$)
agree with kinetic PIC simulations [Gary et al.]

Electrons; [S. Bale]
Stress due to $\Delta p$

anisotropic stress $[\Delta p b_r b_\phi] \sim$ Maxwell stress $[-B_r B_\phi/4\pi]$

$\alpha \approx 0.5$; quite large!

anisotropic pressure $\Rightarrow$ ‘viscous’ heating ($T r_\phi d\Omega / d\ln r$ due to anisotropic stress) at large scales $\Rightarrow$ this goes directly into internal energy!

ion pressure anisotropy limited by IC instability threshold
Will electrons also be anisotropic? Yes, collision freq. is really tiny
electron pressure anisotropy reduced by electron whistler instability
Transport/heating by $\Delta p$

Pressure anisotropy equivalent to anisotropic viscous stress, in addition to Reynolds & Maxwell stresses

\[
\frac{\partial}{\partial t}(\rho V) + \nabla \cdot \left( \rho V V + \left( p_\perp + \frac{B^2}{8\pi} \right) I - \frac{B B}{4\pi} \left( 1 - \frac{p_\parallel - p_\perp}{B^2} \right) \right) = 0
\]

Large scale anisotropic viscous heating, small-scale resistive, viscous heating

\[
\frac{\partial}{\partial t} e + \nabla \cdot (e V + q) = -p_\perp \nabla \cdot V - (p_\parallel - p_\perp) \mathbf{b} : \nabla V + \eta R j^2 + \eta_V |\nabla V|^2
\]

\[
\delta p_{15} = -\frac{p_{05}}{v_5} (3 \hat{b} \cdot \nabla U \cdot \hat{b} - \nabla \cdot \hat{U})
\]

In collisional regime ($\mathbf{u} >> k v_t$), $\Delta p$ reduced by Coulomb collisions

For $\mathbf{u} << k v_t$, anisotropy governed by $\mu$ invariance

$\Delta p$ reduced by scattering by small scale instabilities
Shearing-box energetics

- Work done by anisotropic viscous stress (~50% of energy added to SB)
- Direct plasma heating at box-size scales
- Viscous heating of electrons & ions

- Work done by Maxwell & Reynolds stresses
  \[ k^{-5/3} \]
  Converted to MHD motions \( (\delta V^2, \delta B^2) \)

- Collisionless damping at large scales; nonlinear cascade to small scales
- Dissipation at Larmor radius scales
- Resistive losses at plasma skin depth

- Poorly understood; appears in simulations as grid scale dissipation; e-s or ion heating??
- Non-thermal particles??
Electron heating

In sims. anisotropic heating ~ numerical losses => half the energy is captured as heating due to anisotropic pressure

Form of pressure anisotropy threshold from full kinetic theory for both electrons & ions:

$$\frac{p_\perp}{p_\parallel} - 1 = \frac{S}{\beta^\alpha}$$

Ratio of electron & proton heating rates ($q_e/q_i$, a key qty. in ADAF models)

$\alpha \approx 0.5, S_e \approx 0.4 S_i$ for ion cyclotron/electron whistler instabilities => significant electron heating (compare with Braginskii where ions are heated preferentially)

Results depend on pitch angle scattering thresholds (which are well-tested in the Solar Wind)
Even if electrons are cold initially, viscous heating will eventually give $T_e/T_i \sim 1/(\text{few 10s})$ [synchrotron cooling of e-s not included in sims]
Putting SB in 1-D model

measured electron temperature \( \sim 3 \times 10^{10} \) at \( \sim 24 \, r_S \) \[\text{[Bower et al. 2004]}\]

Electrons quite radiatively efficient w. \( \eta \sim 10^{-3} \) & \( \dot{M} \sim 10^{-7} M_\odot/\text{yr} \)

consistent with Faraday RM observations which give \( \dot{M} < \dot{M}_{\text{Bondi}} \) \[\text{[Bower, Marrone, et al.] \& with global MHD sims.}\]
Conclusions

- Pressure anisotropy natural as $\mu$ conserved
- Scattering due to microinstabilities
- Anisotropic stress $\approx$ Maxwell stress
- Significant $e^-$ heating $\Rightarrow$ hot $e^-$s ($\eta \sim 10^{-5}$ ruled out)
- $\dot{M} < \dot{M}_{\text{Bondi}}$ for low luminosity; consistent with rotation measure toward Sgr A*
Future Work

• Global simulations w. anisotropic pressure & thermal conduction

• 2-species treatment for e⁻s and ions; mildly relativistic EOS for e⁻s; simple radiation model

• Diagnosis of energy flow; phenomenological models of flaring

• Direct comparison w. observations (e.g. T[r])

• Non-thermal acc. still unresolved!

The End