An Introduction to (a small part of) Astrophysical Plasma Physics

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Overview

- Range of Astrophysical Plasmas & Techniques
- Dilute Astrophysical Plasmas
 - Solar Wind
 - Accretion Disks onto Black Holes

• Emphasize Techniques, Questions over Details

Range of Astrophysical Plasmas & Techniques

Non-Relativistic Relativistic Force-Free Force-Free Electrodynamics (e.g., solar corona) (e.g., pulsars) (M)HD (GR)(M)HD (e.g, star formation, disks, galaxy formation) (e.g., BH accretion/jets) gyrokinetics PIC (e.g., turbulence, reconnection) (e.g., rel. shocks) hybrid & PIC (e.g., shocks, reconnection, disks, turbulence) Fluid Models ideal (M)HD (ok first approx?) non-ideal: resistivity, Hall, ambipolar (e.g., star formation) dense multi-fluid: dust + gas/plasma (e.g., planet formation) plasmas radiation (M)HD (e.g., star formation, disks, BH growth)

dilute plasmas non-ideal: anisotropic conduction & viscosity (e.g., galaxy clusters) multi-fluid: pressure tensor & anisotropic conduction (e.g., solar wind, disks) MHD + test particles (e.g., solar wind, corona)

Range of Astrophysical Science Questions

thermodynamics

electron htg, accel (often decoupled from dynamics)

e's dominate radiation from most astro plasmas

ion(~p) htg, accel: (heliosphere, SNe shocks, CRs, jets, ...)

$\rho_i, d_i <<<$ system scale L

turbulent transport due to ~MHD scale instabilities (though modified by non-ideal effects in many cases)

micro-scales dynamically impt if they influence scales ~ L Kinetic-scale physics particularly impt when pressure forces impt:

thermo \leftrightarrow dynamics

dynamics

Solar Corona & Wind



- Corona at $R \sim 2 R_{sun}$
 - $n \sim 10^6 \text{ cm}^{-3}$; $B \sim 1 \text{ G} (\beta \leq 10^{-2})$
 - $T_{ion} >> T_p \sim 2 |0^6 |K| \gtrsim T_e \sim |0^6 |K|$
 - ions: $T_{\perp} \gtrsim T_{\parallel}$ (particularly minor ions)
 - $\ell_{mfp} \sim \text{few } R_{sun} \sim 10^8 \rho_P$

Solar Corona & Wind

- Hydro models predicted solar wind (though $\beta <<1$ and collisionless!) Parker 1958
 - pressure forces accelerate solar wind (slow rotation)
- Heating \leftrightarrow Pressure \leftrightarrow Accel. of Solar Wind
 - Early models invoked e^- conduction but $T_{ion} \gtrsim T_e$ in fast wind
 - Ion Heating Key: Kinetic Physics
 - Htg at all radii: $\sim 1-10^4 R_{\odot}$
- Heating: Alfven wave turbulence (via kinetic AWs; maybe also cyclotron, fast waves)
 - observed in situ & least damped MHD mode in collisionless plasmas
 e.g., Belcher & Davis 1971; Barnes 1956



Matthaeus et al. 1999

Solar Corona & Wind

State of the Art Global Models:

- ID w/ detailed microphysics (or multi-D w/ less microphysics)
- Multi-Fluid: p, e, alpha, minor ions

separate T_{\perp}, T_{\parallel} evolution w/ heat fluxes & \perp , || htg

Waves/Turbulence Dynamically Evolved



kinetic models of htg used in global dynamical models

origin of e, p, ion \perp , || htg still not fully understood

velocity amplitude

Modes of Accretion



luminous BHs: p_{rad} >> p_{gas} GR effects, large-scale B-fields, ...

protostellar disks: ionization state, Hall effect, hydro turbulence?

magnetized disk coronae? ...

(star & planet formation, galaxies, & luminous compact objects)



jet production low M: collisionless T_I/T_e ?

thick disk (~ torus): energy stored as heat (BHs & NSs at low/high accretion rates M)

Galactic Center



observed plasma at ~ 10⁵ R_{horizon}

• $T_e \sim 10^7 \text{ K}$ $n_e \sim 10 \text{ cm}^{-3}$ B $\sim \text{mG}$ (??) $\beta \sim 1$ (??)

macroscopically collisionless

• mfp ~ dist from BH >> R_{horizon}

e-p collision time ~ 10 inflow time

• e conduction time ~ 0.03 inflow time

Galactic Center



- observed plasma at ~ R_{horizon}
 - $L_{synch} \sim R^3 B^2 \gamma^2 n_e \quad v_{synch} \sim \gamma^2 B$
 - Faraday Rotation $\measuredangle \sim \int dl n_e B/\gamma$
- \Rightarrow B ~30 G n_e ~10⁶ cm⁻³ T_e ~10^{10.5} K
 - T_p not directly constrained; believed ~ $10T_e$ $\beta_p \sim 10$
 - macroscopically collisionless

• e^{-} mfp ~10⁷ R_{horizon} ~10¹⁶ $\rho_e!$

BH Accretion Disk Dynamics: Techniques

- A momentum transport by B-fields
 - disk-scale turbulence &/or large-scale B-torques
- Two complementary techniques
 - Global Disk Sims
 - connect to astro phenomenology
 - \mathbf{X} much harder to resolve microphysics
 - Local Shearing Box Sims
 - X missing global context, observables
 - can include & resolve microphysics

Local non-linear evolution of MRI



Balbus & Hawley

BH Accretion Disk Dynamics: Global Sims

- Global Disk Sims
 - Newtonian and GR MHD

connect to astro phenomenologymuch harder to resolve microphysics

 no global sims of low M flows include conduction, viscosity, kinetic effects, multiple-fluids, ... (but ongoing efforts in this direction)



BH Accretion Disk Dynamics: Local Sims

X no global context 🖌 can include & resolve microphysics



eqns expanded in region dR << R about pt in disk

locally Cartesian simulation

w/ or w/out vertical gravity (vertical stratification)

Jake Simon

Local Sims of Other Collisionless Plasmas

X no global context 🖌 can include & resolve microphysics

kinetic instabilities in expanding solar wind



kinetic instabilities in shearing magnetized plasma (e.g., turbulence)

BH Accretion Disk Dynamics: Kinetic Sims

X no global context 🖌 can include & resolve microphysics

- Large-scale dynamics of collisionless plasmas: expand Vlasov eqn using "slow timescale" and "large lengthscale" assumptions of MHD (Kulsrud 1983)
 - more general than the Braginskii eqns
- Particles efficiently transport heat and momentum along B-field lines

$$\begin{split} &\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{V}) = 0, \\ &\rho\frac{\partial\mathbf{V}}{\partial t} + \rho\left(\mathbf{V}\cdot\nabla\right)\mathbf{V} = \frac{\left(\nabla\times\mathbf{B}\right)\times\mathbf{B}}{4\pi} - \nabla\cdot\mathbf{P} + \mathbf{F_g}, \\ &\frac{\partial\mathbf{B}}{\partial t} = \nabla\times\left(\mathbf{V}\times\mathbf{B}\right), \qquad \mathbf{P_{r\varphi}: stress/transport} \\ &\mathbf{P} = p_{\perp}\mathbf{I} + \left(p_{\parallel} - p_{\perp}\right)\mathbf{\hat{b}}\mathbf{\hat{b}}, \end{split}$$

Evolution of the Pressure Tensor

$$\rho B \frac{d}{dt} \left(\frac{p_{\perp}}{\rho B} \right) = -\nabla \cdot (\hat{\mathbf{b}} q_{\perp}) - q_{\perp} \nabla \cdot \hat{\mathbf{b}}$$

adiabatic invariance of $\mu \sim v_{\perp}^2/B \sim T_{\perp}/B$

$$\frac{\rho^3}{B^2} \frac{d}{dt} \left(\frac{p_{\parallel} B^2}{\rho^3} \right) = -\nabla \cdot (\hat{\mathbf{b}} q_{\parallel}) + 2q_{\perp} \nabla \cdot \hat{\mathbf{b}},$$

 $q \sim n \kappa \nabla_{\parallel} T$

closure model: к ~ v_{th}H (saturated conduction)

Pressure Anisotropy

$$\mu \propto T_{\perp} / B = \text{constant} \implies T_{\perp} > T_{\parallel} \text{ as } B$$
 '

- But $T_{\perp} \neq T_{\parallel}$ unstable to small-scale instabilities that act to isotropize the pressure tensor (velocity space instabilities)
 - e.g., mirror, firehose, ion cyclotron, electron whistler, ...
- Generic feature of weakly collisional plasmas (particularly when $\beta \ge 1$)



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- Generic feature of weakly collisional plasmas (particularly when $\beta \ge 1$)
 - e.g., solar wind, galaxy clusters, SN shocks, reconnection
 - For large-scale evolution of astrophysical systems, need to 1. treat using subgrid model 2. use hybrid/PIC instead of fluid

$$\frac{\partial p_{\perp}}{\partial t} = \dots - \nu(p_{\perp}, p_{\parallel}, \beta) [p_{\perp} - p_{\parallel}]$$
$$\frac{\partial p_{\parallel}}{\partial t} = \dots - \nu(p_{\perp}, p_{\parallel}, \beta) [p_{\parallel} - p_{\perp}]$$

local kinetic calcs critical for informing global fluid models

PIC & Hybrid MRI Sims

• First Principles Approach: Particle-in-Cell Sims of Disk Turbulence

- solve for p (and e-) distribution functions + MRI + mirror, firehose, IC
- downside is limited dynamic range & computationally challenging



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Riquelme+ 2012 (Full PIC; 2D)

Range of Astrophysical Techniques, Plasmas, Science

thermodynamics

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ion(~p) htg, accel: (heliosphere, SNe shocks, CRs, jets, ...)

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dynamics of dilute astrophysical plasmas turbulent transport due to ~MHD scale instabilities (modified by non-ideal effects)

micro-scales dynamically impt:

pressure anisotropy feeds back on macro-scales kinetic heating/dissipation sets thermodynamics Large-scale Evolution via (non-ideal, multi-fluid) Fluid Models w/ Kinetic Calcs Critical for Informing Transport, Heating,