Laboratory Astrophysics on the SSX device

Michael Brown

Swarthmore College

with contributions from

M. Kaur, D. Schaffner, T. Gray, C. Cothran (postdocs)
J. Shrock ‘18, E. Lewis ‘18, L. Barbano ’18
K. Gelber ‘20, H. Srinivasulu ’21, M. Membratu ‘21, L. Dyke ‘20… 65 total

SULI Lecture
June 17, 2020

Research supported by DOE APRA and NSF
Laboratory Astrophysics on the SSX device

• Astrophysical examples

• Key physics: turbulence, reconnection, generation of relaxed magnetic structures... these are all coupled in astrophysics

• Some examples from SSX lab
Galactic jet (Hercules A, 1 Mpc)
EHT image of plasma around black hole

$6 \times 10^9$ solar mass black hole, $T = 10^{12}$ K, or 100 MeV
300 AU across
Solar plume (CME) and wind (plasma)

200,000 km

400 km/s plasma with entrained magnetic fields (SDO, 8/12)
Granules 1000 km across, B=0.1T, lanes 30 km across, bright spots possibly small, twisted loop tops emerging every 20 minutes
Turbulence Primer

• Cascade from large scales to small

• Energy dissipated through viscosity and resistivity

• Kolmogorov scaling done on paper
Inverse length, $1/L$

Amount of energy, joules

big

small
Kolmogorov turbulence spectrum (1941)

The graph shows the logarithm of the energy spectrum $E(k)$, with $k$ on the logarithmic scale. The spectrum peaks at $k_0$ and then decreases following a $k^{-5/3}$ law as $k$ approaches $k_v$. The diagram illustrates the transition from big to small scales, with $k_0$ and $k_v$ marking the boundaries.
Kolmogorov spectrum

\[ E(k) = C \varepsilon^\alpha k^{-\beta} \]

\[ E(k) \propto \frac{v^2}{k} \]

\[ \epsilon \propto kv^3 \]

\[ v^2 k^{-1} \propto k^\alpha v^{3\alpha} k^{-\beta} \]

\[ 2 = 3\alpha \]

\[ -1 = \alpha - \beta \]

\[ \alpha = \frac{2}{3} \]

\[ \beta = \frac{5}{3} \]

Depends only on injection rate and k
Energy per mass per wavenumber
Energy per mass per time
Dimensional analysis
Reconnection Primer

• Converts magnetic energy at large scales to flow and heat at small scales ($\rho_i$)

• Particle energization: ions, electrons, both heat and acceleration

• Re-organizes fields again on a large scale

  • Calculation on paper
Reconnection (Sweet/Parker)

\[
\frac{v_{in}}{v_{out}} = \frac{\delta}{L}
\]

\[
B_{in}(4L) = \mu_0 J_z (2L)(2\delta) \rightarrow B_{in} = \mu_0 J_z \delta
\]
The SSX Laboratory

10kV/100kA
Pulsed power

Cylindrical vacuum chamber
(D = 0.5 m, L = 1 m)

High voltage plasma guns on each end
SSX parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Density (protons)</td>
<td>$10^{14}$ - $10^{15}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Temperature ($T_e, T_i$)</td>
<td>20 - 60 eV</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>&gt; 0.1 Tesla</td>
</tr>
<tr>
<td>Ion gyroradius</td>
<td>&lt; 0.5 cm</td>
</tr>
<tr>
<td>Alfvén speed</td>
<td>100 km/s</td>
</tr>
<tr>
<td>S (Lundquist number)</td>
<td>&gt; 1000</td>
</tr>
<tr>
<td>Plasma $\beta$</td>
<td>0.1-1</td>
</tr>
</tbody>
</table>

$\rho \ll R$, so treat as MHD fluid… no intrinsic scale!
Equipartition of flow, thermal, and magnetic energy
Spheromak formation

Stuffing flux acts like a nozzle
Plasma merging scenario (old SSX)

Rapid merging of two rings

Single structure is formed
MHD wind tunnel (since 2014)

• 50 km/s flows, fully ionized and magnetized

• Kinetic, magnetic, thermal energies comparable

  • Single plume (10 kJ)

• Characterization of MHD turbulence

  • MHD simulation
Taylor state formation
SSX MHD wind tunnel
50 km/s, magnetic and fluid turbulence

Diagnose with arrays of magnetic and velocity probes
Diagnostics at midplane (B and $n_e$)

Line-averaged density with He-Ne, temperature from IDS
Ion Doppler spectrometer on SSX

Interferometer chord and two magnetic probes also shown
Mach probe measures local flow
Comparison with predicted helical state

State with the minimum magnetic energy
(subject to certain constraints)
Originally predicted by J. B. Taylor
Trapped proton orbits

Summary

Turbulent relaxation (with magnetic reconnection) shows the emergence of a twisted helical magnetic structure in SSX that is a good trap for protons.

Similar to magnetic structures observed in solar/space plasmas... turbulence, reconnection, heating, relaxation... all related.
Thank you!
Questions?