Electrodynamic coupling processes in the solar–terrestrial environment

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The most notable work is the *Chandrasekhar limit*, which explains that if the mass of a white dwarf star exceeds 1.44 times that of the sun, it would implode.
The pulsar (Bell and Hewish, 1967) radio intensity shows strong scintillations caused by interstellar plasma turbulence. Lee and Jokipii in 1975 developed a strong scintillation theory for wave intensity scintillation, angular broadening and pulse broadening.
Lee and Jokipii proposed that the interstellar turbulent plasma medium has a Kolmogorov-like spectrum ($\sim q^{-11/3}$) with wavelengths extending from $10^8$ m to $10^{18}$ m.

This is confirmed by observations in the past 40 years.

This is a pioneer paper on the turbulent plasma density spectrum in the interstellar space.


Observation 5: Decorrelation bandwidth and angular Broadening (Cordes et al., Nature, 354, 121, 1991)
Voyager 1 left interplanetary space into interstellar medium on August 25, 2012.
The inferred electron density profile can be used to obtain the in-situ power of electron density fluctuations.

Plasma waves measured from December 2011 to October 2016

(Voyager 1)

$q^{-11/3}$

(Lee & Lee, 2017)


Observation 5: Decorrelation bandwidth and angular Broadening (Cordes et al., Nature, 354, 121, 1991)

Observation 6: Voyager 1 (Lee and Lee, 2017)

\[ q^{-11/3}, \text{Lee and Jokipii} \]
(A) Flows in the solar photosphere lead to the formation and eruption of solar prominences.

(B) Transport of particles and energy from the solar wind to magnetosphere through magnetic reconnection.

(C) Magnetosphere-ionosphere coupling leads to magnetospheric substorms, auroras and auroral kilometric radiation.

(D) The micro-scale processes provide electric resistivity for macro-scale magnetic reconnection and ion heating for shocks in collisionless plasma.
A thin elongated structure of cool and dense material suspended in the hot and low density solar atmosphere.

- Red Color
- Observed during solar eclipse
Shear flow leads to the axial magnetic field.
Radiative Cooling

![Graph showing radiative cooling rate as a function of temperature. The x-axis represents temperature (T [K]) ranging from $10^3$ to $10^7$, and the y-axis represents the cooling rate $Q(T) [\text{erg sec}^{-1} \text{ cm}^3]$ ranging from $10^{-24}$ to $10^{-21}$. The graph includes data from Hildner, Rosner et al., and Peres et al.]}
• Choe and Lee proposed the time-dependent formation of solar prominence within a magnetic arcade (near sunspot) with shear plasma flow on the solar surface.

• Prominence mass is found to be supplied through siphon-type flow induced by "thermal instability".
Normal polarity prominences
(Choe and Lee, 1992)

Inverse polarity prominences
(Lee, Choe & Akasofu, 1992)
Shear flow leads to thinning of current sheet
In the presence of resistivity, thin current sheet leads to reconnection/eruption
(B) Transport of particles and energy from the solar wind to magnetosphere provides energy for solar wind-magnetosphere-ionosphere coupling.
Open Magnetopause

Dungey (1961)
Dayside Magnetopause

(a) Single X-line Reconnection:
   RD + Slow Expansion Fan
   Levy et al. (1965)

(b) Flux Transfer Events (FTEs)
   once every ~10 minutes
   Russell and Elphie (1979)
Multiple X-line Reconnection (MXR)

L. C. Lee and Z. F. Fu (1985)
Z. W. Ma et al. (JGR, 1994)
Very large magnetic flux rope observed by THEMIS.

Lui et al. (2008)
(C) Magnetosphere-ionosphere coupling leads to auroras and auroral kilometric radiation.
Reconnection electric field projected to the polar cap: Kan-Lee electric field (GRL, 1979)

(a) Reconnection electric field along X-line: \( E_R = V_S B_S \sin(\theta/2) \)

(b) Component of \( E_R \) perpendicular to geomagnetic field:
\[
E_{KL} = E_R \sin(\theta/2) = V_S B_S \sin^2(\theta/2)
\]
Polar cap potential vs $E_{KL}$

Burke et al., JGR, 1999

$E_{KL}(\text{kV}/R_E)$
(a) Field-aligned potential drop ($\Delta \phi$) enhanced the current carried by magnetosphere electrons (Knight, PSS, 1973).

(b) Field-aligned potential drop ($\Delta \phi$) in the double layer accelerates auroral electrons to $\sim 10$keV, producing aurora.

(c) This potential drop ($\Delta \phi$) prevents ionospheric electrons from entering the double layer, leading to $\omega_{pe}/\Omega_{ce} < 0.3$.

(d) Loss-cone (or horse-shoe) electrons are formed by mirror effects of geomagnetic field.

(e) Auroral kilometric radiation (AKR) is generated by loss-cone electrons in the plasma depleted region.
Auroral Kilometric Radiation (AKR)

- $f \sim 100-600$ kHz (\sim local electron cyclotron frequency)
- X mode dominates
- $\omega_{pe} < 0.3 \omega_{ce}$

[Gurnett, JGR, 1974]
Cyclotron Maser Instability (CMI)

a) Relativistic resonance condition

\[ k_{||}u_{||} - \omega \gamma + n\Omega_c = 0, \quad \gamma = \sqrt{1 + \left( u_{\perp}^2 + u_{\parallel}^2 \right)/c^2} \]

b) Population-inversion distributions:
\[ \frac{\partial f}{\partial u_{\perp}} > 0 \]
Relativistic resonance condition (ellipse)

\[(1 + \frac{u^2}{c^2})^{1/2} \omega_r - \Omega_e - N \cos \theta \omega_r \frac{u_\parallel}{c} = 0\]

\[\frac{u_\parallel}{A^2} + \frac{(u_\parallel - u_\theta)^2}{B^2} = 1\]

Wagner, Lee et al. (Radio Science, 1984)
Radio Emission

1. Sun (1940)

2. Jupiter (1960)
   wave length ≈ 10m, power ≈ $10^{10}$ W

3. Pulsars (1967)

   wave length ≈1000m, power ≈ $10^9$ W

5. Saturn, Neptune, Uranus

6. Exoplanet: auroral radio emission from exoplanet can be used to determine the existence and magnitude of magnetic field
(D) Coupling of micro-process to macro-process

(D1) “Resistivity” for magnetic reconnection in a collisionless plasma

(D2) Ion heating in collisionless fast shock
(D1) “Resistivity” in a Collisionless Plasma


Force Balance at Neutral Lines for Electrons and Ions

\[
- \frac{m_e}{e} \frac{\partial v_y^{(e)}}{\partial t} = E_y + \frac{1}{n_e e} \frac{\partial P_{xy}^{(e)}}{\partial x} + \frac{1}{n_e e} \frac{\partial P_{zy}^{(e)}}{\partial z}
\]

\[
\frac{m_i}{e} \frac{\partial v_y^{(i)}}{\partial t} = E_y - \frac{1}{n_i e} \frac{\partial P_{xy}^{(i)}}{\partial x} - \frac{1}{n_i e} \frac{\partial P_{zy}^{(i)}}{\partial z}
\]

The Generalized Ohm’s Law Near Neutral Line

\[
E_y = \frac{m_e}{e^2} \frac{\partial (J_y / n)}{\partial t} + \frac{m_e}{m_i n e} \left( \frac{\partial P_{xy}^{(i)}}{\partial x} + \frac{\partial P_{zy}^{(i)}}{\partial z} \right) - \frac{1}{n e} \left( \frac{\partial P_{xy}^{(e)}}{\partial x} + \frac{\partial P_{zy}^{(e)}}{\partial z} \right)
\]

Off-diagonal terms of pressure tensor are the key to the “anomalous” resistivity for collisionless magnetic reconnection
Magnetic Field Lines

Off-Diagonal Pressure $P_{xy}$

(a) $\Omega_i t = 0$

(b) $\Omega_i t = 10$

(c) $\Omega_i t = 20$

(d) $\Omega_i t = 30$

(e) $\Omega_i t = 40$

(f) $\Omega_i t = 50$

(g) $\Omega_i t = 60$

(h) $\Omega_i t = 70$

(i) $\Omega_i t = 10$

(j) $\Omega_i t = 20$

(k) $\Omega_i t = 30$

(l) $\Omega_i t = 50$

(m) $\Omega_i t = 60$
"I think your paper marks the breakthrough", by Jim Dungey

(D2) Ion heating in collisionless fast shock

Lee, Wu, and Hu (1986); Lee and Wu (2000); Lee and Lee (2016)
Helium harmonics generated by oxygen bunch distribution
Flows in the solar photosphere lead to the formation and eruption of solar prominences.

Transport of particles and energy from the solar wind to magnetosphere through magnetic reconnection.

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The micro-scale processes provide electric resistivity for macro-scale magnetic reconnection and ion heating for shocks in collisionless plasma.
Thank You

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