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ELECTRIC CONDUCTIVITY OF LOWER SOLAR ATMOSPHERE

JINGXIU WANG
Beijing Astronomical Observatory, Chinese Academy of Sciences

ABSTRACT Electric conductivity tensor of partly-ionized plasma is deduced. Four atmospheric models are used then to estimate the conductivity in the lower atmosphere. The parallel conductivity reaches its minimum value in the temperature minimum zone, which is 1 to 2 orders smaller than the conductivity of fully-ionized plasmas of the same condition; the effective perpendicular conductivity, or Cowling conductivity, becomes 5 to 6 orders smaller than the fully-ionized value in the lower chromosphere.

INTRODUCTION

In solar MHD, a generalized Ohm's Law with a scalar electric conductivity, which is deduced by Spitzer (1962) for fully ionized plasmas, is assumed. However, the lower atmosphere of the sun is only partly ionized (Zirin, 1988), and the strong magnetic field in the plasma makes the conductivity become a tensor instead of a scalar. *How does the real conductivity in the lower atmosphere deviate from the Spitzer value?* The answer is crucial to the understanding of magnetic field evolution.

Based on Cowling's three fluid theory, we deduced the conductivity tensor for a partly ionized plasma permeated by a magnetic field. Then, the Harvard-Smithsonian Reference Atmosphere (Gingerich et al., 1971), the VAL Atmosphere Model (Vernazza et al., 1976), the Photospheric Reference Model and Umbral Core E Model presented by Maltby et al. (1986) are used to estimate the electric conductivity for solar photosphere and lower chromosphere. Finally, the result is briefly discussed in light of interpreting observations.

CONDUCTIVITY TENSOR OF PARTLY IONIZED PLASMAS

For a given point, when a coordinate system whose z axis is parallel to the magnetic field $\vec{B}$ is chosen, and the general Ohm's Law is written in the form of

$$\vec{j} = \overleftrightarrow{\sigma} \cdot \vec{E}_\circ, \tag{1}$$

the conductivity tensor of partly ionized plasmas can be expressed as

$$\overleftrightarrow{\sigma} = \begin{pmatrix} \sigma_\perp & -\sigma_T & o \\ \sigma_T & \sigma_\perp & o \\ o & o & \sigma_\parallel \end{pmatrix} \tag{2}$$

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where,

$$\begin{aligned}\sigma_\perp &= \sigma_o(p+q)^{-1}[1+r^2(p+q)^{-2}]^{-1},\\ \sigma_\top &= \sigma_\perp r(p+q)^{-1},\\ \sigma_{||} &= \sigma_o p^- 1,\end{aligned} \tag{3}$$

and, $\sigma_o = \frac{n_e e^2 \tau_{ei}}{m_e}$ is the scalar conductivity for fully-ionized plasmas.

Here, the '||', '⊥' are referred to currents which are parallel and perpendicular to the direction of the magnetic field, respectively; while, '⊤' is for the Hall current which is perpendicular to both the magnetic field and electric field $\vec{E}_o$.

$$\vec{E}_o = \vec{E} + \vec{v} \times \vec{B} \tag{4}$$

where, $\vec{v}$ is the velocity of the mass.

The p, q, r are functions of plasma parameters:

$$\begin{aligned}p &= 1 + \frac{m_i\tau_{ei}}{m_i\tau_{en}+2m_e\tau_{in}},\\ q &= f^2\varpi_e^2\tau_{ei}\tau_{en}\frac{2m_e\tau_{in}}{m_i\tau_{en}+2m_e\tau_{in}},\\ r &= \varpi_e\tau_{ei}(1-\frac{4fm_e\tau_{in}}{m_i\tau_{en}+2m_e\tau_{in}}),\end{aligned} \tag{5}$$

where, $\varpi_e = \frac{eB}{m_e}$ and $f = \frac{n_e}{n_a+n_e}$, τ stands for the mean interval between successive collisions of two species of plasmas. The other symbols have their usual meanings, and the subscripts 'e', 'i', and 'n' always refer to electrons, ions and neutral atoms.

The resistance tensor is the reversion of $\overleftrightarrow{\sigma}$:

$$\overleftrightarrow{\rho} = \begin{pmatrix} \frac{\sigma_\perp}{\sigma_\perp^2+\sigma_\top^2} & \frac{\sigma_\top}{\sigma_\perp^2+\sigma_\top^2} & o \\ -\frac{\sigma_\top}{\sigma_\perp^2+\sigma_\top^2} & \frac{\sigma_\perp}{\sigma_\perp^2+\sigma_\top^2} & o \\ o & o & \sigma_{||}^{-1}\end{pmatrix}. \tag{6}$$

The dissipation of electric current would be

$$\vec{j}\cdot\vec{E} = \vec{j}\cdot[\overleftrightarrow{\rho}\cdot\vec{j}] = \frac{j_\perp^2}{\sigma_\perp^*} + \frac{j_{||}^2}{\sigma_{||}} \tag{7}$$

where, $\sigma_\perp^* = \sigma_\perp + \frac{\sigma_\top^2}{\sigma_\perp}$ is the Cowling conductivity, or effective perpendicular conductivity, which determines the dissipation of perpendicular current.

The following approximations are useful for a practical evaluation of the conductivity for an atmosphere.

$$\frac{m_e\tau_{in}}{m_i\tau_{en}} \sim (\frac{m_e}{m_i})^{1/2} \tag{8}$$

from Spitzer (1968); and

$$\frac{\tau_{ei}}{\tau_{en}} \simeq 5.2\times10^{-11}(\frac{1-Z}{Z})\frac{T^2}{ln\Lambda} \tag{9}$$

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from Priest (1982), where, Z is the ionization degree of the plasma, Λ is the Coulomb logarithm. The τ_{ei} is estimated from Spitzer (1962)

$$\tau_{ei} = 0.266 \times 10^6 \frac{T^{3/2}}{n_e ln\Lambda}. \quad (10)$$

THE CONDUCTIVITY OF THE LOWER ATMOSPHERE

The Harvard-Smithsonian Reference Atmosphere (HSRA), the VAL Atmosphere Model, the Photosphere Reference Model (PRM) and Umbral Core E Model (UCM) are used to estimate the electric conductivity for solar photosphere and lower chromosphere from equations (2 - 3), (5) and (8 - 10).

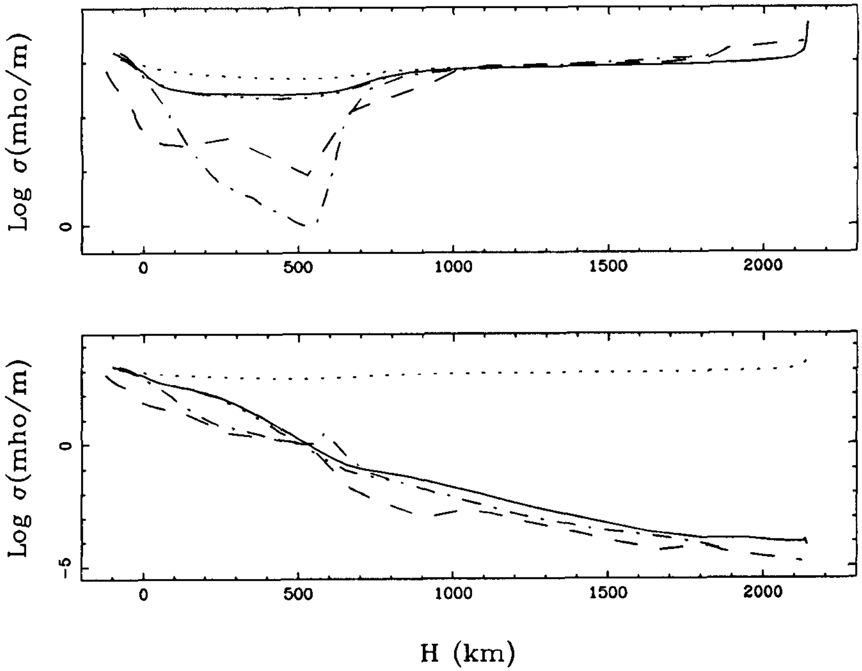

Fig.1. The parallel and effective perpendicular conductivities in the lower atmosphere.

The calculated parallel conductivity and Cowling conductivity are shown in the upper and lower parts of Figure 1, respectively. The dotted line is the conductivity for fully-ionized plasma, i.e., the Spitzer value, when the electron and temperature distributions are the same as PRM; it serves as a reference for comparison. The conductivity shown by the dash-dotted line is the result

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for HSRA. The dashed line is for UCM. The result for VAL is presented by dot-dot-dot-dashed line; the PRM, the solid line.

The parallel conductivities from HSRA and UCM deviate obviously from the Spitzer value. In the temperature minimum zone, they are 1 to 2 orders smaller than the latter. However, no big differences from the Spitzer value are found for the results of PRA and VLA models. Unlike the case for parallel conductivity, the Cowling conductivities for all four atmospheric models decrease with increasing height, and reach very low values in the lower chromosphere, almost as low as an insulator. This is caused by the term comprising q which results in a contribution proportional to B^{-2}. When its contribution is relatively large,

$$\frac{\sigma_\perp}{\sigma_\circ} \propto \frac{n_e^2}{(1-Z)ZTB^2}. \tag{11}$$

It is also seen that $\sigma_\perp$ might reach its minimum value when the ionization degree is close to 1/2.

SUMMARY

(1). As an asymmetric tensor, the conductivity in the lower atmosphere can not be properly described by a scalar value for a fully-ionized plasma.

(2). It seems that the Ohmic diffusion of the magnetic field in the lower atmosphere can not be fully ignored. For example, if the Sweet-Parker reconnection is a basic process involved in the observed flux cancellation, the conductivity in the temperature minimum zone might be small enough to account for the rate of flux disappearance.

(3). One possibility is suggested that if there are mechanism or mechanisms of generating perpendicular electric currents in the lower chromosphere, the Ohmic diffusion might be fast enough to heat the atmosphere, or even trigger flares in virtue of very low Cowling conductivity.

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