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论文题目：多成份太阳风模型

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中文摘要

太阳风被发现近半个世纪以来，一直成为日地空间物理学界普遍关注的前沿和热点问题之一。虽然理论模型和观测手段都取得了非常大的进展，但关于太阳风是如何被加速和加热的问题仍然是没有彻底解决的跨世纪难题。申请人着重选取了太阳风物理中若干具有代表性的前沿课题展开工作，针对不同的太阳风之典型观测特征建立理论模型，通过拟合飞船或卫星的观测数据以及对计算结果的分析来理解相关的太阳风物理过程。

(1) 建立了以阿尔文波为唯一外加能源的二维电子、质子太阳风磁流体模型。假定波能量由低频阿尔文波向高频离子回旋波串级，再经回旋共振将波能转移给太阳风质子；波耗散率取为 Kolmogorov 率形式。在子午面内得到了“高纬高速流－低纬冕流、电流片与低速流”典型结构。计算得出高、低速流中都可存在幅度相当的阿尔文波，与 Helios 飞船的观测一致；阿尔文波的波能耗散机制可作为驱动高速流与低速流太阳风的物理机制。一维计算表明，之所以高低速流具有截然不同的物理特性可能与其流管几何密切相关，这一点与 Wang and Sheeley (1990) 早期根据光球磁场的源面外推模型推论是一致的。

(2) 为了解释太阳和日球观测台紫外日冕仪(SOHO/UVCS)的最新观测结果，作者构造了回旋共振机制驱动的三成份 (电子、质子及 O5+ 离子) 近日低速流太阳风模型。假设离子回旋波由低频阿尔文湍流通过 Kolmogorov 率串级产生，波粒相互作用之准线性理论及考虑质子色散效应的冷等离子体色散关系被用来在质子与 O5+ 离子之间分配耗散的回旋波波能。计算结果与最近太阳和日球观测台紫外日冕仪沿一冕流轴线对 O5+ 离子参数的观测数据以及熟知的 1 AU 处质子的质量通量平均值相吻合，表明通常用于解释冕洞高速流太阳风离子观测特性的回旋共振机制对于低速流太阳风中离子特性的形成也可能有重要作用。发现 O5+离子流速随径向距离增加呈非单调变化，在冕流尖点附近存在一低于目前观测精度的速度极小值 (也见 Chen 等, 2004, ApJ)。这种低速流离子的非单调变化的速度剖面被作者定义为太阳风离子的“滞流现象”。

(3) 同一元素不同电荷态间的差动速度被用来解释高速流中实测之高电荷态分布与根据太阳和日球观测台发射辐射紫外测量仪 (SUMER/SOHO) 的谱线数据导出的冕洞低电子温度

之间的矛盾。但是电荷态间差动速度存在的可能性及其大小演化等情况仍是未知。为研究差动速度的情况及其在离子形成过程中的作用，我们同时求解了同一元素 (C, O, Mg, Fe 和 Si) 五种电荷态离子的质量、动量及能量方程，考虑了离子的电离复合过程及其与背景太阳风等离子体的库仑碰撞耦合作用。模型还考察了改变能量注入对差动速度的影响。发现差动速度在一定日心距离 (～1.2 太阳半径) 之外，但在相当一部分离子形成之后才可以发展起来，所以仅仅使用差动速度无法解释上述高电荷态分布与低电子温度之间的矛盾。

(4) 假设太阳风高速流中电子由环分量及核分量两种成份组成，我们建立了首个双电子流体高速流太阳风模型，以模拟高速流电子速度分布函数的主要观测特征。计算表明，若只考虑库仑碰撞相互作用，则环电子高温对应于一很强的热压梯度力，导致其漂移速度远大于相应观测值。为抑制环电子的漂移速度必须引入由诸如微观不稳定性及波粒相互作用引起的异常摩擦 (即异常输运现象)。为模拟这些异常输运现象，本模型使用增强的库仑碰撞相互作用，并增加对环电子分量的能量注入。发现在一定日心距离以远(>20 太阳半径)，作用于环电子之上的异常摩擦力比相应电场力和库仑摩擦力都更为重要，成为抑制两种电子流体之间相对漂移速度的主要因素。

关键词：高速与低速太阳风、离子回旋共振机制、少数离子电荷态、电子速度分布函数

Multi-fluid solar wind models

Chen Yao

ABSTRACT

We develop a novel two-dimensional two-fluid magnetohydrodynamic solar wind model taking Alfvén waves as the only external energy source. In the model the wave energy is assumed to cascade from low-frequency Alfvén waves to high-frequency ion cyclotron waves and to be transferred to the solar wind protons by cyclotron resonance at the Kolmogorov rate. A typical coronal configuration is obtained in the meridional plane, consisting of a coronal streamer at lower latitudes, a fast wind at high latitudes, and a slow wind across the heliospheric current sheet. It is shown that the Alfvén waves appear in the fast- and slow-wind regions simultaneously and have comparable amplitudes, which agrees with Helios observations. The Alfvén waves may be taken as an efficient driving mechanism for both the fast and slow winds. With the one-dimensional models it is also demonstrated that the distinct properties of the fast and slow winds can be attributed to different flow-tube geometries, a conclusion agreeing with the early model proposed by Wang and Sheely (1990).

A cyclotron-resonance driven theoretical model for a three-fluid slow wind consisting of electrons, protons and O^{5+} ions is established for the first time. The ion-cyclotron waves are assumed to be produced by the Kolmogorov turbulence cascade of the low-frequency Alfvén waves. The quasi-linear theory of the wave-particle interaction and the cold plasma dispersion relation of the ion-cyclotron waves are employed to distribute the dissipated wave energy among ions. It is predicted that the O^{5+} outflow speed varies non-monotonically with increasing heliocentric distance. There is a local minimum of the outflow speed near the streamer cusp point, which is below the current observational sensitivity. This type of ion outflow in the slow solar wind is termed “stagnated outflow”. By reproducing recent measurements on the O^{5+} parameters along a streamer axis and the well-known average proton mass flux in the slow wind near the Earth, it is shown that the gyro-cyclotron resonance mechanism proposed to explain the observations in the coronal hole and fast wind may also be important to the ions in the slow solar wind.

Extremely large differential flow speeds between ions of the same element have been proposed to reconcile the high charge states observed in situ in the fast solar wind and the low electron temperature deduced from SUMER/SOHO spectral measurements in the coronal hole. However, it remains unknown whether differential flows exist between charge states and how they evolve with radial distance. To address this issue and investigate the effect of differential flow speeds on the ion formation, we solve simultaneously the mass, momentum and energy equations for the charge states of C, O, Mg, Si and Fe (e.g., 15 sets of equations for Si), including the ionization and recombination processes, and the collisional coupling with the background solar wind plasma. The effect of varying heat inputs is also considered. It is found that differential flow speeds between ions of the same element do develop beyond a certain heliocentric distance (about 1.2 *Rs*). However, this is beyond the region where a substantial fraction of minor ions form, and the differential flow speeds with a low electron temperature near the Sun cannot account for the high ion charge states observed in situ.

To simulate the main characteristics of the observed electron velocity distribution function, we construct the first fast solar wind model containing two electron populations. It is assumed that the solar wind electrons are composed of two fluid components: core and halo, which is in agreement with observations carried out in situ in the solar wind. It is shown that in the case including only Coulomb collisions the high temperature of the halo electrons produces a strong thermal pressure gradient force, which yields a much faster halo drift than observed. To inhibit the halo drift, anomalous transport processes caused by micro-instabilities and/or wave-particle interactions must be included in the model. We show that these anomalous frictional processes can be approximated by enhanced Coulomb collisions together with more heat input. We find that beyond a certain heliocentric distance, approximately 20 *Rs*, the anomalous frictional forces acting on the halo population are more important than the electric field force and the Coulomb collisional forces, and become the dominant factor inhibiting the core-halo drift.

Key words：fast and slow solar winds, ion-cyclotron resonance mechanism, minor ion charge states, electron velocity distribution functions