MHD Waves in Energy Balance of the Solar Wind and the Solar Corona

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(Received October 31, 1994; Accepted November 14, 1997)

Estimations are presented concerning the contribution of MHD waves propagating from the low boundary of chromosphere-corona transition layer in the energy balance of magnetically open outer solar atmosphere. The corresponding energy-momentum sources are shown to be sufficient for coronal heating and solar wind acceleration. Selfconsistent model of wave driven solar corona and solar wind is constructed, in the frame of which the locations of coronal temperature maximum and solar wind transonic region coincide with the regions of effective wave damping. Wave energy flux into the corona is controlled by the value of magnetic field induction at the coronal base, and the wave energy distribution into the main channels of losses is determined by the magnetic field structure in the inner and middle corona.

1. Introduction

The main problem of outer solar atmosphere is the problem of energy source for coronal heating and solar wind acceleration. As deduced from the known observational data and their comparison with theoretical models this source must satisfy the following requirements. First of all, it must be sufficient to provide energy balance of the solar corona. Estimating coronal radiative losses, work against gravitational forces and solar wind energy, one can find the corresponding energy flux into the corona $H^* > 10^5$ erg cm$^{-2}$s$^{-1}$ (Hundhausen, 1972). Secondly, the initial source of energy flux is located at photospheric level near the outer boundary of the solar convection zone. Thus, the mechanism of energy transmission through the chromosphere must be effective enough to provide necessary energy flux. Finally, additional energy source acting beyond the corona, up to solar wind critical point at least, is necessary, as the heat conduction from the corona is not sufficient to form the plasma flow with the measured energy and mass fluxes (Hundhausen, 1972). To all appearance, only MHD waves satisfy all these conditions. Indeed, it is difficult to provide sufficient energy flux using slow photospheric motions with which non-wave heating mechanisms are connected. Besides that, such electrodynamics mechanisms of heating as currents damping and coronal magnetic fields reconnection may be effective only in the inner corona and can not be extended to large heliocentric distances.

2. Wave Flux into the Corona

We shall consider MHD waves excited by convective noise and propagating away from the Sun in the open magnetic regions. Three wave models are possible in magnetized near-Sun plasma: fast (f) and slow (s) magnetosonic and alven (a) with phase speeds max ($v_s, v_a$), min ($v_s, v_a$) and $v_a$ correspondingly, were $v_s$ is the sound speed and $v_a$ is alven speed. Turbulence in the chromosphere is strong and nearly isotropic. It is dominated by f-mode as the plasma parameter $\beta = v_s^2/v_a^2 > 1$. Turbulence in the upper chromosphere is generated by waves propagating from the lower regions. Wave flux into the corona is formed at the bottom of the transition layer (heliocentric distance $r_*$, pressure $p_*$) between the chromosphere and the corona. The condition of strong turbulence allows to connect the value of energy flux with the induction $B_*$ of regular magnetic field. Isotropic fast mode is strongly reflected by transition layer; a- and s-modes are reflected weakly, but their relative level in the corona will be small because of sharp
gradient of phase speeds in transition layer. As the wave flux into the corona is dominated by a- and s-waves, we have the following estimations of entering wave energy flux (Chashei and Shishov, 1987).

\[ H_\ast = H^a + H^s = \eta \cdot \frac{B^2}{4\pi} \cdot v_s, \quad \text{if } \beta_\ast > 1 \]  
(1)

\[ H_\ast \approx H^a = \eta \cdot \frac{B^2}{4\pi} \cdot v_s \sqrt{\beta_\ast}, \quad \text{if } \beta_\ast < 1 \]  
(2)

were \( \eta = 0.6 \) is the transmission coefficient of the transition layer, \( \beta_\ast = \frac{v_s}{v_a} \). The additional flux attenuation between the \( \beta = 1 \) level and the transition layer is taken into account in \( \beta_\ast < 1 \) regime. This attenuation can easily suppress the value of \( H_\ast \). We can see from estimations (1), (2) that the maximum value of energy flux is reached at \( \beta_\ast = 1 \):

\[ H_{\ast,\text{max}} = \eta \cdot \frac{B^2}{4\pi} \cdot v_s. \]  
(3)

At \( B_\ast \geq 2 \, G, \, T_\ast \approx 10^4 \, K \) we have \( H_\ast \geq 10^5 \, \text{erg cm}^{-2}\text{s}^{-1} \), that is in a good agreement with the value required for coronal energy balance. For the considered mechanism of energy flux formation energy containing frequency \( \omega_0 \) is of order of \( \omega_0 = 2 \cdot 10^{-2} \, \text{s}^{-1} \) (period \( T_0 = 5 \, \text{min} \)) and defined from the condition \( \lambda_0 = h_\ast \), were \( \lambda_0 \) is wavelength, \( h_\ast \) is the typical scale of hydrostatic atmosphere.

It should be noted that some authors, see, for instance, (Athay and White, 1979), have argued, that observed wave flux in the upper chromosphere is not sufficient for coronal energy balance. However, as it was shown in the paper of Chashei and Shishov (1986), the wave flux, obtained form the UV lines data, is strongly underestimated.

3. Selfconsistent Model of Solar Wind and Solar Corona Formation by Wave Energy Source

The energy source, connected with wave flux (1), (2) was used by developing of the wave model of coronal heating and solar wind acceleration (Chashei and Shishov, 1988). The model is based on the whole system of MHD equations and includes the wave terms in the momentum and energy equations as the selfconsistent forces and heating sources. Energy-momentum sources arise when we add the equations describing wave propagation with linear and nonlinear damping taking into account. Boundary conditions for wave model are specified at the initial level \( r_* \), at the infinity and in the solar wind critical point. Partially, boundary conditions (1), (2) allows to connect the wave sources with the regular magnetic field \( B_* \) at the coronal base. The model takes into account mutual influence of the solar wind and the solar corona. The position of coronal base \( r_* \) and the solar wind mass flux are not fixed beforehand but must be determined from the solution. The only free parameter for a given flux tube which defines the coronal and solar wind regimes is the magnetic field induction \( B_* \) at the coronal base.

4. Wave Energy Distribution in the Channels of Coronal Losses

The source of coronal heating is the collisional damping of propagating away alfven and slow magnetosonic waves. This damping is most effective near the region \( r = r_m \), were energy containing frequency \( \omega_0 \) is equal to frequency \( \nu_i \) of ion-ion collisions. Slow magnetosonic waves and high frequency, \( \omega \geq \omega_0 \), alfven waves are fully absorbed in the corona, giving rise to heating with coronal temperature maximum at \( r = r_m \).

Corresponding part of initial energy flux
MHD Waves in Energy Balance of the Solar Wind and the Solar Corona

\[ H_*^{\text{dis}} = H_*^a + \xi \cdot H_*^b = H_*^+ + H_*^- \]  

(4)

due to the heat conduction is distributed on fluxes \( H^- \) directed to coronal base and \( H^+ \) directed to the outer corona. The flux \( H^- \) provides the work against gravitational forces \( H_{g^*} \) and radiative losses \( p^*u_0 \) (\( u_0 = 5 \cdot 10^5 \text{ cm/s} \))

\[ H_* = H_{g^*} + p^*u_0. \]  

(5)

The heat conduction flux \( H^+ \) is the coronal source of the outer corona heating. Additional \( H^+ \) energy source in the outer corona is connected with low frequency, \( \omega < \omega_0 \), alfven waves, for which corona is transparent. Additional energy flux is equal to

\[ H_*^{\text{add}} = (1 - \xi) \cdot H_*^a \]  

(6)

and their nonlinear damping results in the acceleration and heating of the solar wind, which is most effective near the solar wind critical point. According to estimations the critical point is located at heliocentric distance \( r_0 = 10r_* \), and fast plasma acceleration by waves takes place in comparatively narrow region between \( 10r_* \) and \( 20r_* \).

5. Typical Values of the Corona and Solar Wind Parameters

Several simple models for initial magnetic field were considered in the frame of developed approach: spherically symmetric model (SS), isolated coronal hole (ICH) and quasidipole magnetic field (QDMF). We present below typical plasma parameters estimated by appropriate values of \( B^* \): maximum temperature of the corona \( T_m \), plasma \( \beta^* \) at the coronal base, the ratio \( \xi \) of dissipated in the corona alfven flux to entering one, asymptotical solar wind speed \( V_{sw} \).

| Model     | \( B^* \) (G) | \( \beta^* \) | \( T_m \) (10^6 K) | \( \xi \) | \( V_{sw} \) (km/s) |
|-----------|---------------|---------------|---------------------|---------|---------------------|
| SS        | 3             | 1             | 2                   | 0.8     | 400                 |
| ICH       | 7             | <1            | 1.3                 | 0.5     | 700                 |
| QDMF (pole)| 5             | <1            | 1.3                 | 0.5     | 700                 |

6. Conclusions

The above consideration shows that wave energy flux is sufficient to provide the energy balance of the corona and the solar wind. Moreover, the properties of waves and plasma are strongly connected: chromosphere-corona transition layer is the region of wave flux regulation, coronal temperature maximum is the region of effective collisional damping of alfven and slow waves, solar wind transonic point and acceleration zone near it correspond to the region of effective nonlinear damping of low frequency alfven waves. The main conclusions of the self-consistent wave model are in a good agreement with the observational results, partially with the radio-occultation data: Faraday fluctuations measurements shows the presence of outwardly propagating alfven waves with frequencies \( \omega \leq \omega_0 \) in the region between several
and 10 solar radii (Efimov et al., 1993); it follows from radioscintillation data, that the solar wind critical point is located near 10\(r_s\), just in the inner part of the region of additional acceleration (Efimov et al., 1990). The model explains high solar wind speed and low coronal temperature above the coronal holes and above the heliolatitude dependence of the solar wind velocity in the activity minimum (Watanabe et al., 1974).

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