ELECTRON THERMAL CONDUCTION AS A POSSIBLE PHYSICAL MECHANISM TO MAKE THE INNER HELIOSHEATH THINNER

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ABSTRACT

We show that electron thermal conductivity may strongly affect the heliosheath plasma flow and the global pattern of the solar wind’s interaction with the local interstellar medium. In particular, it leads to strong reduction of the inner heliosheath thickness, which makes it possible to explain (qualitatively) why Voyager 1 (V1) has crossed the heliopause at an unexpectedly small heliocentric distance of 122 AU. To estimate the effect of thermal conductivity, we consider a limiting case when thermal conduction is very effective. To do that, we assume the plasma flow in the entire heliosphere is nearly isothermal. Due to this effect, the heliospheric distance of the termination shock has increased by about 15 AU in the V1 direction compared with the adiabatic case with $\gamma = 5/3$. The heliospheric distance of the heliopause has decreased by about 27 AU. As a result, the thickness of the inner heliosheath in the model has decreased by about 42 AU and has become equal to 32 AU.

Key words: conduction – solar wind – Sun: heliosphere

Online-only material: color figures

1. INTRODUCTION

Stone et al. (2013) and Krimigis et al. (2013) reported a sudden drop in the fluxes of the heliospheric energetic particles and a substantial increase in the galactic cosmic-ray fluxes in 2013 August at a heliocentric distance of $\sim$122 AU. Such behavior of the energetic particle fluxes could be due to Voyager 1 (V1) crossing the heliopause. Such a conclusion has not been made, however, because the magnetic field did not change direction (Burlaga et al. 2013) as might have been expected since it is very improbable that the direction of the interstellar magnetic field is the same as that of the heliospheric magnetic field.

Gurnett et al. (2013) analyzed the V1 kHz emission event that occurred in 2013 April and showed that the registered radio frequency gives an estimate for the plasma number density of 0.08 cm$^{-3}$. This estimate is substantially larger than the solar wind (SW) number density and corresponds to the expected density in the interstellar medium. Therefore, Gurnett et al. (2013) concluded that V1 was inside the LISM in 2013 and crossed the heliopause in 2012 August.

The V1 crossing of the heliopause at 122 AU was not expected by a part of the heliospheric community since the global models of the SW/LISM interaction suggest that the thickness of the inner heliosheath in the V1 direction should be of the order of 50–70 AU depending on the model (see, e.g., Izmodenov et al. 2013). Several ideas for resolving this problem have appeared in the recent literature. For instance, Borovikov & Pogorelov (2014) suggested that the smaller distance is connected with the instabilities of the heliopause while Schwadron & McComas (2013) argued for an interstellar flux transfer effect and Swisdak et al. (2013) claimed that the observed behavior could be explained by magnetic reconnection in the inner heliosheath and at the heliopause.

Here it is worth noting that there are theories suggesting that V1 is still inside the heliosphere (Baranov 2013; Fisk & Gloeckler 2014). For the rest of this paper, we assume that the crossing occurred at 122 AU and estimate how the effect of thermal conduction influences the plasma flow in the inner heliosheath and the positions of the termination shock and heliopause. The importance of electron thermal conduction in the heliosheath plasma flow has been recently pointed out by Baranov & Ruderman (2014); they have shown that this is the most important dissipative process. The relative importance of thermal conduction is characterized by the Peclet number, $\text{Pe} = k_B n_e L V / k$, where $k_B$ is the Boltzman constant, $n_e$ is the electron number density, $L$ is the characteristic spatial scale of the problem, $V$ is the characteristic plasma speed, and $k$ is the coefficient of the parallel thermal conduction.

When $\text{Pe} \gg 1$, the effect of thermal conduction can be neglected, whereas it is very important when $\text{Pe} \lesssim 1$. Baranov & Ruderman (2014) have estimated that $\text{Pe} \approx 5$ in the outer heliosheath and $\text{Pe} \lesssim 1$ in the inner heliosheath. Hence, we can expect that the effect of thermal conduction is more pronounced in the inner heliosheath than in the outer one.

2. PROBLEM FORMULATION, NUMERICAL METHOD, AND BOUNDARY CONDITIONS

We consider the interaction of the SW with the local interstellar medium (LISM) using a kinetic hydrodynamic approach. In accordance with this approach the plasma component is described by the ideal magnetohydrodynamic (MHD) equations, while the neutral component is described using the kinetic equation. The latter equation is solved using the Monte Carlo method. To solve the ideal MHD equations, we use a finite-volume high-order Godunov scheme that includes a three-dimensional adaptive moving grid with discontinuities and capturing and fitting capabilities, namely a Harten–Lax–van Leer Discontinuity MHD Riemann solver and a Chakravarty–Osher TVD procedure. A detailed description of the equations and numerical method can be found, e.g., in Izmodenov et al. (2009).
In our calculations, we have used the following values for the parameters in the LISM and SW. In the LISM: the proton number density is \( n_{p,\text{LISM}} = 0.06 \) cm\(^{-3}\), the H-atom number density \( n_{\text{H,\text{LISM}}} = 0.18 \) cm\(^{-3}\), the temperature of both the plasma and neutral component \( T_{\text{LISM}} = 6530 \) K, the velocity \( V_{\text{LISM}} = 26.4 \) km s\(^{-1}\), the magnetic field magnitude \( B_{\text{LISM}} = 4.4 \mu\text{G} \), and the angle between the velocity and magnetic field angle \( (B,V) = 20^\circ \). In the SW, we imposed boundary conditions at 1 AU: a spherical SW without a magnetic field with a proton number density of \( n_{E} = 7.39 \) cm\(^{-3}\), a radial velocity of \( V_{E} = 432 \) km s\(^{-1}\), and a plasma temperature of \( T_{E} = 67,800 \) K.

To consider the thermal conduction, we need to include the corresponding term in the energy equation. To do this, we need to modify substantially the Godunov method that we use. Another complication is related to the fact that in the presence of a magnetic field, the thermal conduction is strongly anisotropic. The heat flux is mainly directed along the magnetic field, but the heat flux perpendicular to the magnetic field is almost completely suppressed. To avoid complications but still estimate the effect of thermal conduction, one could consider a limiting case of isothermal flow in the entire heliosphere. The isothermal flow corresponds to a case of very strong thermal conduction when Pe \( \ll 1 \). Mathematically, the isothermal flows of perfect gases correspond to flows with a polytropic index of \( \gamma = 1 \). It follows from the Clapeyron equation that the pressure \( P \) and density \( \rho \) are related by \( P = \rho RT \), with a temperature \( T = \text{const} \). The adiabatic motion of the plasma is described by the ideal MHD equations with the pressure and density related by \( P \propto \rho^\gamma \), where \( \gamma \) is the adiabatic index. For fully ionized plasmas \( \gamma = 5/3 \). The adiabatic and isothermal flows are two limiting cases of negligible and very strong heat conduction. Comparing these two cases would give us an estimate of the possible thermal conduction effect on the plasma flow in the SW/LISM interaction region.

Since consideration of the isothermal flow requires significant modification of our numerical code, we consider instead nearly isothermal polytropic flow in the entire heliosphere (i.e., the region inside the heliopause) with \( \gamma = 1.06 \). The reason why we did not use \( \gamma = 1 \) is purely technical: our numerical code does not allow \( \gamma = 1 \). The effect of thermal conduction in this case would be slightly smaller than in the exactly isothermal case, but it is sufficient enough to be useful for the goals of this paper. For the outer heliosheath (i.e., the region outside of the heliopause) we assume \( \gamma = 5/3 \).

We should emphasize that we do not pretend that this simplified approach describes the effect of thermal conduction correctly in actual detail. We only hope that our simple model gives a numerical estimate of how the thermal conduction influences the global size and shape of the heliospheric interface.

3. NUMERICAL RESULTS

In this section, we present the results of our numerical calculations. Figure 1 presents the locations of the termination shock and heliopause for the models with \( \gamma = 1.06 \) (solid curves) and \( \gamma = 5/3 \) (dashed curves) in the inner heliosheath. It is seen that in the model with \( \gamma = 1.06 \), the termination shock moves out and the heliopause moves in compared with what happens in the other model. This is an expected effect of the thermal conduction that leads to a substantial reduction of the temperature and thermal pressure in the heliosheath (especially on the upwind side). Figure 1 also shows the isolines of the plasma temperature for the model with \( \gamma = 1.06 \). It is seen from the figure that in the entire heliosphere the temperature is nearly constant \((\sim 1.2–3 \times 10^5 \) K\).

It is interesting to note that despite \( \gamma = 1.06 \) being close to one and the supersonic SW being close to isothermal, there is a temperature jump at the TS. This result directly follows from the Rankine–Hugoniot relations at the shock for the gas with \( \gamma = 1.06 \).

Figure 2 displays the dependence of the plasma density, pressure, total pressure (plasma plus magnetic), temperature, and radial velocity on the heliospheric distance in the VI direction. The blue dashed lines correspond to the case where \( \gamma = 5/3 \) everywhere, while the red solid lines correspond to the case where \( \gamma = 1.06 \) inside the heliopause. This figure allows us to determine directly that the distance from the Sun to the termination shock increases by about 15 AU in the VI direction, while the distance from the Sun to the heliopause decreases by about 27 AU. As a result, the thickness of the inner heliosheath decreases by about 42 AU and becomes only 32 AU.

4. SUMMARY AND CONCLUSIONS

In this Letter, we have studied the effect of thermal conduction in the inner heliosheath on the plasma flow and the positions of the termination shock and heliopause. To simplify the problem, instead of taking into account the term describing the thermal conduction in the energy equation, we have modeled nearly isothermal flow by reducing the polytropic index to \( \gamma = 1.06 \) when describing the flow of the heliospheric plasma inside the heliopause. The main effect of this reduction is the following. The heliospheric distance of the termination shock has increased by about 15 AU in comparison with the case where \( \gamma = 5/3 \).
Figure 2. Dependence of the plasma density, pressure, total pressure, temperature, and radial velocity on the heliospheric distance in the V1 direction. The black lines correspond to the case where $\gamma = 5/3$ was taken everywhere, while the red lines correspond to the case where $\gamma = 1.06$ in the inner heliosheath.

(A color version of this figure is available in the online journal.)

everywhere. The heliospheric distance of the heliopause has decreased by about 27 AU. As a result, the thickness of the inner heliosheath has decreased by about 42 AU and become equal to 32 AU.

Our simplified model demonstrates that the account of thermal conduction strongly influences the plasma flow in the SW/LISM interaction region and the positions of the TS and HP. Therefore, more complex models, including anisotropic thermal conduction effects are needed to analyze data obtained by Voyager 1 and Voyager 2 and the IBEX spacecraft, to understand the SW/LISM interaction, and to investigate the role of electrons as a separate fluid in this context, as already considered in a paper by Chalov & Fahr (2013).

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