THEORETICAL INTERPRETATION OF TRAVELING INTERPLANETARY PHENOMENA AND THEIR SOLAR ORIGINS

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ABSTRACT

Recent theoretical studies on Traveling Interplanetary Phenomena (TIP) and their relation or presumed relation to their solar origins will be reviewed. An attempt is made to outline the theoretical studies in the context of mathematical methods and physical processes. The following alternative approaches are examined: analytical vs. numerical methods; magnetohydrodynamics vs. hydrodynamics; processes with or without dissipation; continuum (macroscopic) vs. the kinetic (microscopic) approach. In particular, the flare-generated interplanetary shocks are used as examples to illustrate these theoretical studies within the context of TIP. Some emphasis will be placed on MHD wave propagation through the inner corona and its maturity to a fully-developed interplanetary shock. Further, their propagation and the disturbing effects on the solar wind will be considered. Cases concerning the classification and characteristics of blast-produced shocks and long-lasting ejecta are also discussed in the context of numerical simulations.

In this review, it has been revealed that: (i) sophisticated numerical simulations are significant for the progress of hydrodynamical and magnetohydrodynamical studies; (ii) these numerical simulation studies have improved significantly the understanding of non-linear mode-coupled wave interactions from the lower corona to interplanetary space; and (iii) lack of emphasis on the kinetic (microscopic) approach limits our understanding on microscopic interactions. We suggest, therefore, that future directions should emphasize the physical processes of the continuum approach (i.e., hydrodynamics and MHD theory) and the kinetic approach to reveal further understanding of microscopic interactions.

I. INTRODUCTION

A large amount of data about transient phenomena in the corona and its extension into interplanetary space has been accumulated by the space program during the past decades. In order to gain basic physical

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insight from these data, theoretical interpretation of them has become a necessity. An attempt is made in this paper to summarize the theoretical studies in the context of mathematical methods and physical processes.

Significant progress in our understanding of traveling interplanetary phenomena has been made. In particular, the study concerning solar flare generated interplanetary shocks has been reported in several recent reviews by Hundhausen (1972a,b), Burlaga (1974), Dryer (1974, 1975) and Wu et al. (1977). Although the present discussion will refer to these earlier papers, consideration of the theoretical interpretation since that time will be emphasized. The purpose of this paper, then is to outline some fundamental developments in the last few years. Accordingly, it will be assumed that the reader has some familiarity with earlier works which are referred to in the reviews noted above. An attempt will be made to categorize these recent developments. Thus, the following approaches are examined: analytical vis-à-vis numerical methods; magnetohydrodynamic (MHD) vis-à-vis hydrodynamic description; macroscopic (continuum) vis-à-vis microscopic (kinetic) approach. Thus, we shall begin our discussion with the macroscopic theory (i.e., the MHD and hydrodynamic descriptions) in Section II with those models using analytical methods in which the discussion of physical regions (i.e., corona/corona-interplanetary) are included. In Section III, we shall discuss the recent developments of microscopic theory in this area. In the final Section IV, current research and future directions of this line of research are discussed.

II. MACROSCOPIC (CONTINUUM) THEORY

In this approach, the coronal and the corona-interplanetary media have been represented by fluid models. Thus, the hydrodynamical and magnetohydrodynamical formalisms are applied. The problems can be classified into two categories: (i) corona and (ii) corona-interplanetary space in order to distinguish two cases of basic physical behavior. For example, in the corona, the initial steady-state can be approximately represented by an isothermal and hydrostatic equilibrium atmosphere where the low subsonic and sub-Alfvénic velocities may be neglected. However, in the corona-interplanetary case, the initial steady-state atmosphere must include the characteristics of the solar wind together with its imbedded magnetic field. That is, the initial state is an atmosphere in hydrodynamic equilibrium instead of in isothermal and hydrostatic equilibrium as in the case of the corona. The mathematical methods used to solve these problems are either analytical or numerical in nature, with each approach complimentary to the other.

II.1. Analytical Analysis

II.1.A Corona. It is well known that the most spectacularly-observed traveling phenomenon in the corona is the so-called "Coronal Transient." These transient phenomena are seen in white light and, in some cases, in X-ray and radio wavelengths (MacQueen et al., 1974);

Stewart et al., 1974; Rust and Hildner, 1976). Some progress has been made toward the theoretical interpretation of these phenomena. In essence, these theoretical studies can be summarized into two categories. The first theoretical approach views coronal transients as a global wave phenomenon (Nakagawa, Wu and Han, 1978; Wu et al., 1978; Steinolfson et al., 1978; Dryer et al., 1979). The method used for this approach utilizes numerical analysis of the complete nonlinear MHD equations and will be discussed later. An alternative interpretation suggested by Mouschovias and Poland (1978) views coronal transients as expanding flux tubes in the corona (1.6 ~ 6 $R_\odot$; $R_\odot$ being the solar radius). In their model, the latter workers assume that a white-light loop-like transient density enhancement seen by the coronograph is a magnetic flux tube which originates below the occulting disk of the coronograph (1.6 $R_\odot$). The flux tube is assumed to expand through a background coronal plasma and magnetic field. This global background atmosphere remains unaffected by the transient. In this model, shown in Figure 1, the material and field within the loop does not bear any relation to the surrounding coronal material and field. The force responsible for the outward expansion of the loop is the magnetic buoyancy force which is local in

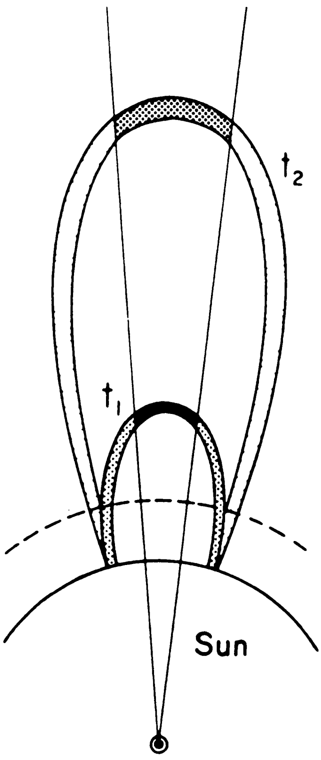

Figure 1. Schematic representation of a coronal loop transient at two different times, t_1 and t_2 (Mouchovias and Poland, 1978).

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nature. Mouchovias and Poland (1978) made a comparison between the observed 1973 August 10 coronal transient event and their model, with some reasonably good phenomenological agreement. The main deficiency of this model is its lack of interaction between the loop and coronal background. Nevertheless, it will be interesting to pursue models such as this one further (Anzer and Poland, 1979). Another example of a model of traveling coronal phenomena which deserves attention is the magnetic reconnection model given by Kopp and Pneuman (1976). In this model, they examined the theoretical consequences during the extended relaxation phase which must follow events such as flares, flare sprays, and eruptive prominences. This phase is characterized by a gradual reconnection of the outward-distended field lines. It is further shown that the enhanced coronal expansion which occurs on open field lines just before they reconnect appears adequate to supply the large downward mass flow observed in the H_α loop prominence systems during the post-transient relaxation phase. In addition, this enhanced flow may produce nonrecurrent high speed streams in the solar wind after such events. Again, the disadvantage of this model is that the lack of systematic approach prevents a complete description of dynamics of the problem which is expected by an analytical method. In fact, a more systematic numerical study has been carried out recently by Steinolfson and Wu (1979), which is being presented in this symposium. The reader is referred to that paper in this Proceedings. The works of Anzer (1979), Syrovatskii and Somov (1979) and Somov and Syrovatskii (1979), as reported in this symposium, should also be noted. They have discussed the driving forces for physically-meaningful coronal response models.

<u>II.1.B. Corona – Interplanetary Space</u>. The required governing equations to describe the physics of these problems are highly nonlinear. Thus, the most appropriate method used to seek an analytical solution is the similarity analysis. A self-similar treatment of a spherical magnetohydrodynamic disturbance for the propagation of interplanetary shocks limited to the vicinity of the equatorial plane of an axisymmetric geometry is presented by Lee and Chen (1968), for the special case where the upstream density behaves as r^{-2}; r being the radial distance. Recently, significant progress in this area has been made by Rosenau and Frankenthal (1976, 1978) and Rosenau (1977, 1978). They extended the treatment of Lee and Chen (1968) to cases where the ambient density behaves as r^{-w}, with $0 \leq w < 3$. This extension is significant. It reveals that the case $w = 2$ is isolated in the sense that the infinitesimal departures from this value result in qualitative changes in the nature of the flow, thereby revealing significant physical meaning for interpretation of interplanetary shock structures. Rosenau and Frankenthal (1978) studied the same problems further by considering a thermally conducting medium. They showed that the motion consists of a thermal precursor followed by an isothermal shock. The magnetic field plays a fundamental role. These workers showed that a very modest transverse magnetic field depresses the peak density, blocks the heat flow, and widens the perturbed domain. Figure 2 (plasma parameters) and 3 (magnetic field) show a comparison of observed data (Heos-1 data on

March 25, 1969) with theoretical predictions based on an adiabatic magnetohydrodynamic model (Dryer, 1974) and an MHD model which incorporates heat conduction. In these results, a significant improvement of the theoretical predictions is demonstrated by including heat conduction. Rosenau and Frankenthal (1978), also noted that the heat conduction is a variable parameter which can be used together with a variable length of the thermal precursor to improve the prediction of the shock structure.

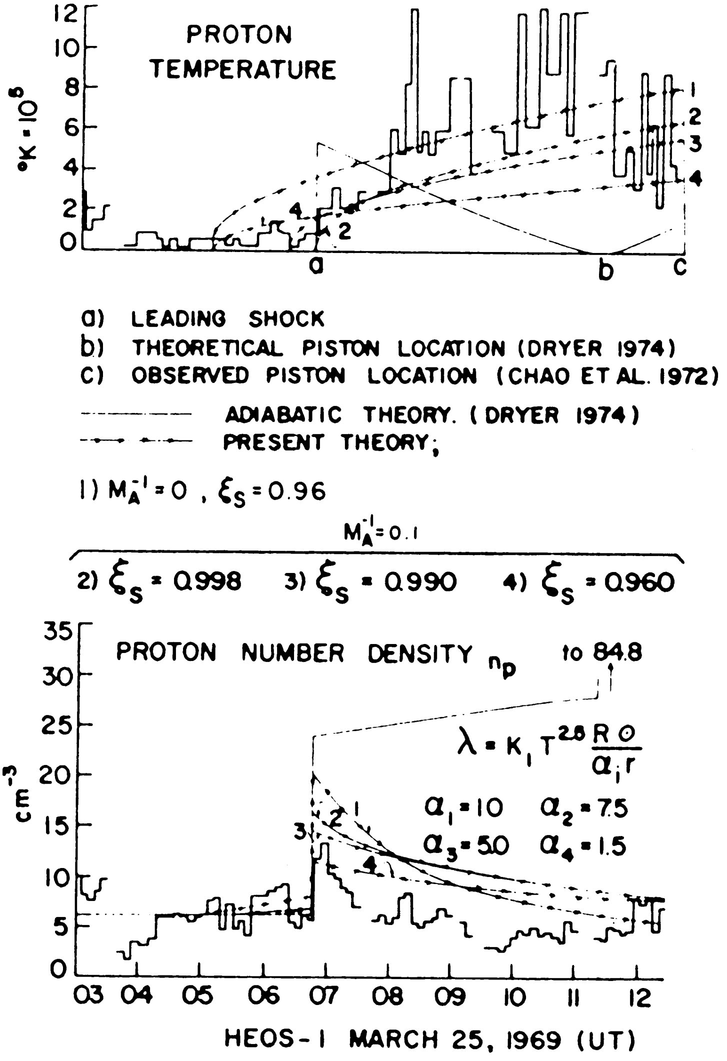

Figure 2. A comparison of observed data (Heos-1 on March 25, 1969) with theoretical predictions based on adiabatic magnetohydrodynamic model and on the model which incorporates heat conduction, λ, as a variable parameter together with a variable length of the thermal precursor ξ_s (Rosenau and Frankenthal, 1978).

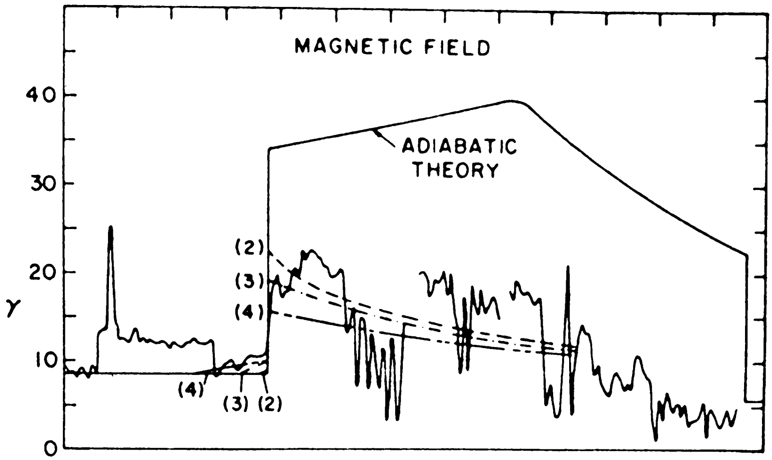

Figure 3. Display of observed magnetic field versus theoretical predictions with same parameters as in Figure 2 (Rosenau and Frankenthal, 1978).

In summary, we conclude that these investigations represent substantial progress on the self-similar theory by its application to the study of the propagation of an axisymmetric magnetohydrodynamic shock in a thermally conducting medium. All these solutions are classified as piston-driven shock solutions, and double pair shocks are revealed.

On the other hand, Summer (1975) investigated an MHD blast-wave type solution applied to a flare-produced shock in the solar wind by using similarity analysis. Similar analysis without the magnetic field but with a gravitational field was done by Rao and Purohit (1973). A pure gasdynamic model using Lagrange-function approach to investigate the geometric characteristics of propagation of the interplanetary shocks was presented by Krimsky and Transky (1973). Dryer (1970) also used the similarity analysis to study the electrical field effect (with finite resistivity) on the propagation of solar flare-induced interplanetary shock waves. He found the largest effects of joule heating (with implied location of turbulence) to be concentrated within the piston region. However, this class of solution is restricted to small magnetic Reynold's number flow. Dryer (1972) has extended this work with finite magnetic Reynold's number flow with anomalous electric conductivity to study interplanetary double-shock ensembles. He has shown that even substantial joule heating has little effect on the gross features of the double-shock ensemble.

II.2. Numerical Analysis

Because of the limitations of similarity analysis on multidimensional, time-dependent problems wherein arbitrary input conditions are prescribed at the boundary, numerical analysis has become an important tool to interprete and understand the physics of the observed

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coronal and corona-interplanetary transient phenomena. Again, we shall divide our discussions into two parts: corona and corona-interplanetary space.

II.2.A. Corona. A recent review concerning numerical modeling of coronal and interplanetary responses to solar events has been given by Wu, Nakagawa and Dryer (1977). In this work, a detailed account of the development of numerical modeling of transient phenomena in these two regions has been presented. Hence, this work will not be repeated.

In a recent development, Steinolfson et al. (1978) presented a boundary perturbation type MHD model in the meridional plane in contrast to the equatorial plane model given by Nakagawa et al. (1978) and Wu et al. (1978), with the later two works having been done in the context of the blast-wave-type solution. Steinolfson and Wu (1979) recently applied this model with Helmet streamer magnetic field configuration to study the coronal response. In the studies mentioned above, the perturbations are considered to be in the nature of a thermodynamic pulse (i.e., changes in temperature, density or both). Recently, Steinolfson et al. (1979) presented a solution with an emerging magnetic flux perturbation. This work shows a distinct result in comparison with a thermodynamic pulse. They found that there exists a high (i.e., β greater than one) region between the shock and contact surface and a low β (less than one) region behind the contact surface (β being the ratio of plasma pressure to magnetic pressure). Dryer et al. (1979) used this model to simulate the 1973 August 21 coronal transient event by using observed plasma parameters (i.e., employing data from S-056 soft X-ray experiment by NASA/MSFC and Aerospace Corporation on board Skylab) as an initial and long lasting pulse. They demonstrated very good agreement with observed data. The outcome of each of these calculations depends strongly on the value of β. Figure 4 shows the β distribution before and after the 1973 August 21 event. The essence of the numerical method for these calculations can be found in the works of Nakagawa and Steinolfson (1976) and Han, Wu and Nakagawa (1979).

As the reader may note, this plane model exhibits the non-linear interaction between fast and slow mode MHD waves; however, the Alfvén mode (transverse wave) is excluded. In order to relax this deficiency, a two-dimensional, time dependent, non-plane, MHD model has been presented recently by Nakagawa et al. (1979), and Wu et al. (1979b). In the work of Nakagawa et al. (1979), a new way of interpreting the energy storage and release in repeated flares was suggested.

II.2.B. Corona-Interplanetary Space. In the previous section, we have summarized briefly the recent development of numerical models for the corona. We will now discuss the current status of modeling in the corona-interplanetary case. Typical results for this problem can be found in the work of Dryer et al. (1976, 1978) and Zakaidakov and Synakh (1977). These workers used a one-dimensional, time-dependent MHD model to study the evolution of the structures of the interplanetary shocks. Also, Dryer et al. (1978) utilized this model to simulate

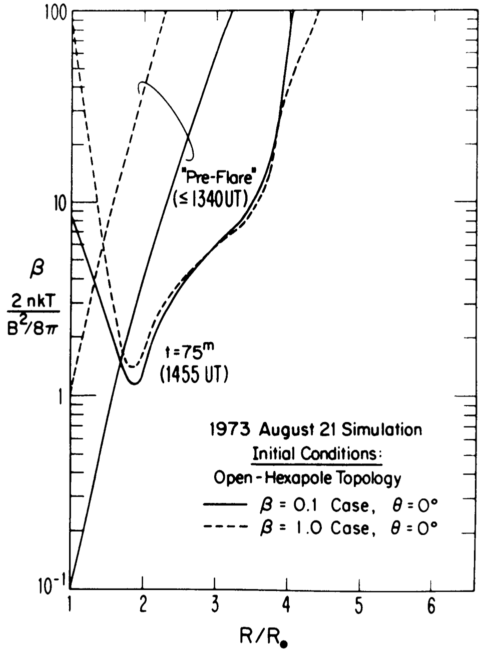

Figure 4. The distribution of β (the ratio of plasma pressure to magnetic pressure) through the solar atmosphere before and after the 1973 August 21 event.

essential features of space-probe data. In particular, the shock pair ensembles are reproduced by these numerical solutions. Wu et al. (1979a) extended their model (Wu et al., 1978) to the corona-interplanetary case by including the solar wind characteristics in the initial state. In this work, they considered the case of stream-stream interactions. Typical results for the disturbed density and temperature contours from the lower corona (18 R_s being solar radius) to 1 A.U. (Astronomical Units) are depicted in Figure 5. This figure shows development of MHD shocks in two dimensions. In a subsequent paper by D'Uston et al. (1979), they utilized this model to study the nonsymmetric properties of the propagation of flare interplanetary shocks. Figure 6 shows their numerical results for the evolution of the position of the forward shock and the reverse shock. The non-spherical nature of the shock front is clearly exhibited.

III. MICROSCOPIC (KINETIC) THEORY

In this context, one treats the problem from a particle point of view, in which the Boltzmann transport equation is used as the basis of the formulation. Practically very little work has been done in the

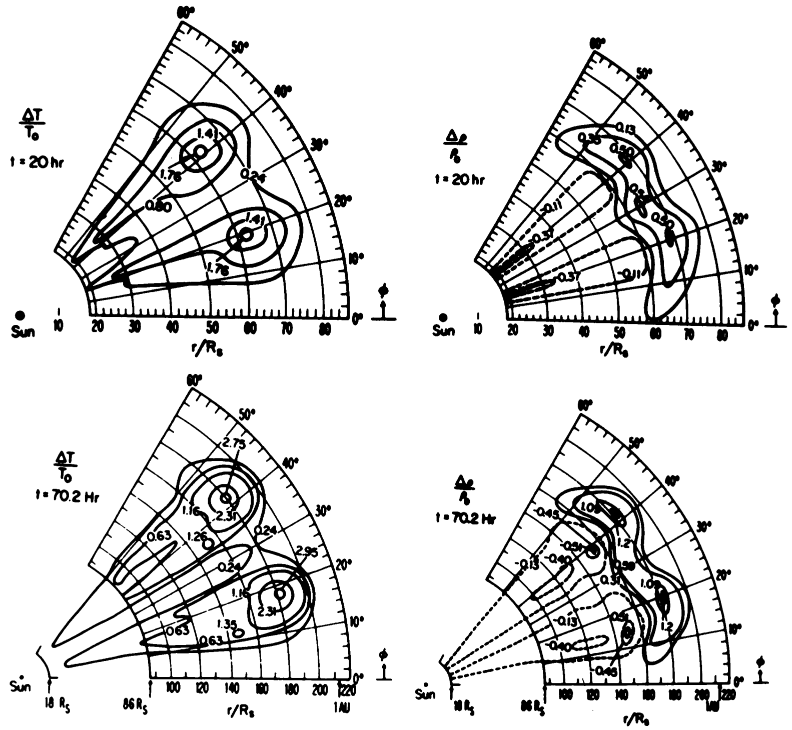

Figure 5. Disturbed temperature enhancement contours $(\frac{\Delta T}{T_o})$ and density enhancement contours $(\frac{\Delta\rho}{\rho_o})$ in the solar equatorial plane at (a) 20 hr and (b) 70 hr after the introduction of disturbance. In the density contours, the solid line represents positive enhancement (i.e., compression), and the broken line represents negative enhancement (i.e., rarefaction) (Wu et al., 1979).

study of transient phenomena in the corona and corona-interplanetary space by using kinetic theory. However, significant advancement of plasma kinetic theory has been made in fusion research in recent years. For example, Liewer and Krall (1973), have used such a method to study the electromagnetic turbulence in fusion plasmas. In the area of solar and interplanetary dynamics, Jockers (1970) presented a solar wind solution by using kinetic theory via the moment method; Fahr, Bird and Ripken (1977) used the moment equations from the collisionless Boltzmann equation to study the solar wind expansion with spherically symmetric magnetic fields. Smith (1971, 1972a,b) used the kinetic theory to study the plasma radiation from collisionless MHD shock waves in the corona and its application to Type II radio bursts. All these results refer to steady state solutions. It is understood that, the classical approach (i.e., Chapman-Enskog method) to seek solution of Boltzmann equation is only limited to the case in which the gradients of the thermodynamical property are small and only particle-particle collision

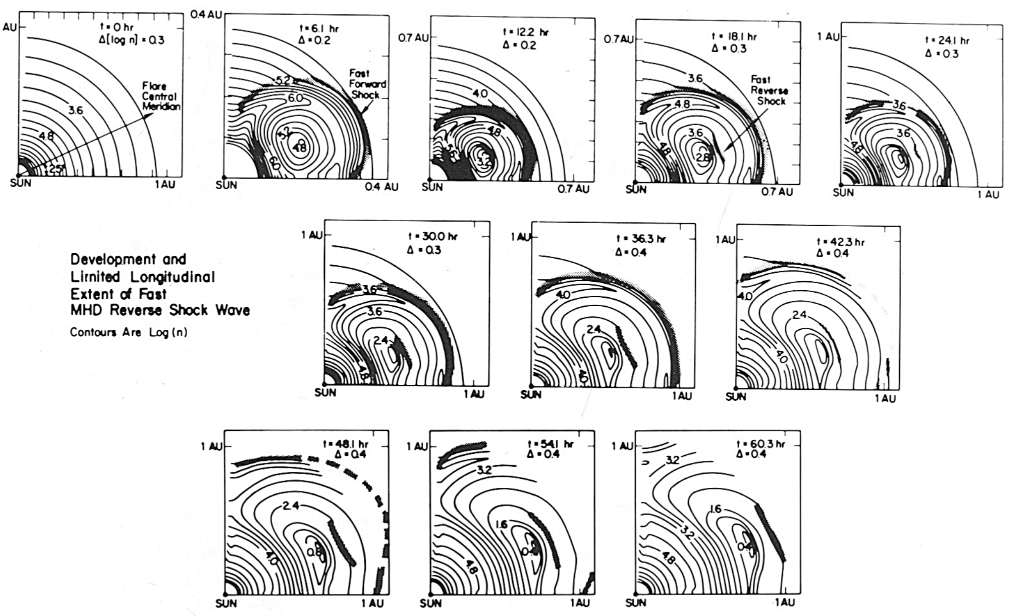

Figure 6. Contour maps of Log(n) showing the development and the extension of the shock fronts from the Sun's surface to 1 A.U. (D'Uston et al., 1979).

is accounted for. In the heliospheric region, the collective behavior of the medium depends not only on the particle-particle collision ρ, but also on the wave-particle interaction. Therefore, a new approach is needed to understand the more realistic physical behavior of the TIP in the corona and corona-interplanetary medium. In this symposium, Cuperman (1979) has suggested such a theoretical study. In his study, higher order moments equations (i.e., fluid description) are developed with more realistic closure conditions and transport coefficients; these transport coefficients are obtained from quasi-linear kinetic theory.

Concerning numerical analyses of the Boltzmann transport equation for transient phenomena in the corona and corona-interplanetary environments, little work has been done because of the mathematical complexity involved. Again, significant progress can be found in fusion research. Also, Wu and Dryer (1972) used a time dependent Boltzmann equation to study the solar wind interaction with celestial objects via numerical methods, however, only particle-particle interaction is taken into account in their collision integrals and a Maxwellian distribution function is also assumed in their computation. Recently a more advanced numerical analysis of kinetic theory has been done by Scudder and Olbert (1978) to explain the observed characteristics of the electron distribution function in the solar wind. Their results are in agreement with observations. All these works indicate that this approach is a promising one.

The inter-relationship between the macroscopic (fluids) theory and microscopic (kinetic) theory is shown in Table I, in which the various levels of sophistication of both approaches with their corresponding physical interpretation are outlined. It should be noted that the current status of the macroscopic approach is far more advanced than the microscopic approach. However, we note the advantages of using the microscopic approach to interpretate the physical behavior of the TIP.

IV. CONCLUDING REMARKS

In summary, this study has revealed that:

(i) Sophisticated numerical analyses are significant for the progress of hydrodynamical and magnetohydrodynamical studies without dissipative processes.

(ii) These numerical studies have improved significantly the understanding of non-linear mode-coupled wave interactions from the corona to interplanetary space.

(iii) The similarity analysis brought significant progress to the understanding of the MHD shock-disturbed flow. However, due to its limitation to a single spatial dimensional configuration and inability to treat realistic boundary conditions, only simple geometry and asymptotic solutions can be studied. Nevertheless, similarity theory is complementary to the numerical studies.

(iv) Lack of emphasis on the microscopic approach limits our understanding of detailed microscopic interactions which have essential effects on macroscopic dynamics, such as the plasma turbulent structures observed in the corona and heliospheric space.

In conclusion, we suggest that future research directions should emphasize the physical processes of the macroscopic (continuum) approach together with the kinetic approach to reveal further understanding of the microscopic interactions. Consequently, a hybrid model for the TIP in the corona and corona-interplanetary space should be constructed.

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TABLE 1. PARALLELISM BETWEEN MACROSCOPIC AND MICROSCOPIC DESCRIPTIONS UNDER VARIOUS LEVELS OF SOPHISTICATION

Order of the Level of Sophistication	Physical Interpretation	Model Description	
		Macroscopic	Microscopic
Zeroth	System at complete thermodynamic equilibrium is steady, homogeneous.	System is in hydrostatic equilibrium with no motion.	Distribution function f is Maxwellian with constant uniform temperature $f^{(o)}$.
First	System at local-thermo-dynamic equilibrium.	System can be represented by a single fluid. Hydro-dynamic and magnetohydro-dynamic (MHD) description applied, no dissipation process.	Distribution function f is local Maxwellian $f^{(o)} = f^{(o)}(n, \vec{u}, T)$ where $n = n(\vec{r}, t)$, $\vec{u} = \vec{u}(\vec{r}, t)$, $T = T(\vec{r}, t)$.
Second	Multiple component system at local thermodynamic equilibrium.	System should be repre-sented by multi-fluids. Hydrodynamic and MHD description applied.	Distribution function f is local Maxwellian for each specified species; $f_s^{(o)} = f_s^{(o)}(n_s, \vec{u}_s, T_s)$; where $n_s = n_s(\vec{r}, t)$; $\vec{u}_s = \vec{u}_s(\vec{r}, t)$; $T_s = T_s(\vec{r}_s, t)$.
Higher Order	Multiple component system at non-local-thermo-dynamic equilibrium.	System will be repre-sented by dissipative multi-fluids system. Hydrodynamic and MHD description applied.	Distribution function for each species becomes highly non-Maxwellian $f_s = f_s^{(o)} + f_s^{(1)}$.

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DISCUSSION

Somov: Magnetic field in the internal (low) corona is a very important energetic factor. Magnetic force can dominate over all other forces. What do you think about the possibility that magnetic field is a primary reason for fast plasma motions in corona?

Wu: Magnetic field is an important force to control the dynamical behavior of the corona. However, the other factor being equally important is the dynamics itself which has been shown in these numerical calculations. These calculations, however, do not consider the *initial* conversion of magnetic energy into kinetic and thermal forms as, for example, you and Prof. Syrovatskii have discussed in various works. Once such conversion takes place, the subsequent mass motion must respond (non-linearly) to the time-dependent interplay of the relative magnitudes of inertial, thermal and magnetic forces. Thus, we may conclude that the essential factor to control the dynamical behavior in the post-flare corona is the plasma motion and magnetic field *interaction*. Consideration of $\beta(t)$ implies the importance of the modulating effect of the magnetic field.

Ivanov: What do you think about including electromagnetic turbulence in hydromagnetic theory?

Wu: To include turbulence in hydromagnetic calculation is a necessary step to be taken to improve our physical interpretation of the observations. However, we have no self-consistant theory to describe hydromagnetic turbulence. This is why I am suggesting the construction of a *hybrid* model. Using kinetic theory to obtain such microscopic turbulent structure is the first essential step. Having done so, one may then put these results into macroscopic theory to construct new models. See Liewer and Krall (1973) for some work along this line.

Unidentified: (Comment) The fact that we see a type II radio burst associated with interplanetary shocks inevitably points to a non-Maxwellian electron distribution. The presence of Langmuir waves in such sources cannot be explained otherwise.

Lemaire: I believe there is much more work done in the kinetic approach than mentioned in your review. For instance: Lemaire and Scherer, *JGR*, 1971 and *Rev. Geophys.*, 1974; Hollweg, *JGR*, 1971; Lemaire (Proceedings of Toulouse Meeting), 1978 March; and Scudder and Olbert, *JGR*, 1979. I consider, for instance, that the recent work by Scudder and Olbert, including collisions as a post-exospheric approximation is the right way to go in future solar wind modeling!

Wu: I think you would agree that it is difficult (nor is it my intention to attempt) to list all publications in this review. I completely agree with you, as I have mentioned in my presentation, that the kinetic approach is *one* of the ways to improve our modeling effort. The work by Scudder and Olbert is one of several approaches (referenced in the text) currently under consideration. Whether it is, as you say, "the right way to go" is a matter of subjective opinion. It should be considered (in my opinion) to be an open question and not one which excludes alternative considerations (see, for example, Prof. Cuperman's review, this Proceedings).