THE EFFECT OF A CORONAL SHOCK WAVE ON THE
SOLAR WIND IONIZATION STATE

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ABSTRACT

The solar wind ionization state is "frozen" within a few solar radii of the photosphere, and measurements of the ions at 1 AU can therefore potentially yield information about conditions (e.g., electron temperature) at the base of the coronal expansion. In the active solar corona, intrinsic time variations can be as important as variations associated with flow through spatial gradients in determining the frozen-in ionization state. We illustrate that, by using a Lagrangian approach of following individual fluid parcels, the techniques used for calculating ionization state variations in a steady state case can be straightforwardly extended to time-varying flows, if the flow speeds of the different ion stages are the same.

Sample calculations performed here for the specific case of a strong shock propagating at constant speed through the corona show that only fluid parcels shocked at or below the ambient freezing-in radius have their ionization state significantly modified by the shock. For fluid parcels shocked below this freezing radius, the degree of ionization initially increases sharply because of heating at the shock front, but it then declines because of adiabatic cooling with the outward expansion; the asymptotic degree of ionization for such parcels can actually be lower than for the unshocked ambient flow. Parcels shocked near the freezing-in radius show less of an initial response to the heating than those shocked lower, but they are already frozen-in during the cooling phase and thus have a moderately enhanced asymptotic degree of ionization. Time-dependent ionization effects for the sudden transition between two otherwise steady flows are thus likely to be limited to a narrow range of gas parcels which, having been shocked within the coronal freezing-in radius, pass a fixed interplanetary observer in an interval of a few times 10 minutes. Furthermore, the amplitude of any rise in interplanetary ionization temperature associated with a coronal shock is likely to be considerably smaller than the jump in electron temperature that actually occurs in the corona.

Subject headings: hydromagnetics — shock waves — Sun: corona — Sun: solar wind

I. INTRODUCTION

The solar wind ionization state is "frozen" within a few solar radii of the photosphere, and in situ measurements of the heavy-ion charge states by interplanetary spacecraft can therefore potentially yield information about conditions (e.g., electron temperature) at the base of the solar coronal expansion (Hundhausen, Gilbert, and Bame 1968a, b). Although this expansion is inherently variable, previous studies of the ionization state freezing have been based on the simplifying assumption that changes in a given fluid parcel arising from its flow through spatial gradients dominate intrinsic time variations, which are thus neglected (e.g., Bame et al. 1970, 1974, 1979; Holzer and Axford 1970; Lange and Scherb 1970; Fenimore 1980; Ogilvie and Vogt 1980; Owocki, Holzer, and Hundhausen 1983, hereafter Paper I). Although this is reasonable for the "quiet" solar wind, intrinsic time variations in the corona (e.g., coronal shock waves or mass ejection events) may strongly influence the ionization state of interplanetary gas observed in association with solar activity (Bame et al. 1979; Fenimore 1980), and so interpretation of these observations should take into account the effect of such intrinsic variability. In this paper, we shall illustrate that, by using a Lagrangian approach of following individual fluid parcels, the techniques used previously for calculating ionization state variations in a steady state case (see Paper I; also Owocki 1982) can be straightforwardly extended to time-varying flows. The specific ionization state calculations presented here will be for a relatively simple picture of time-dependent coronal flow, based on a well-known model of a self-similar shock wave propagating through the corona, but the same technique is applicable to any flow with equal flow speeds $u_i = u_s$ for all ionization stages $i$ of species $s$, given the time and spatial variations in electron density, ion velocity, and electron temperature.

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Our simplified approach will serve to illustrate a basic physical limitation to the ionization effects caused by coronal time variations and to place bounds on the amplitude and duration of the ionization effects that might be observed in the time-dependent solar wind.

The participation of the corona in solar activity had long been suspected on the basis of both in situ measurements of the solar wind and white-light observations of the solar corona. Measurement of large and abrupt shifts in solar wind conditions in association with large solar flares (Hundhausen 1972a, b) suggested the propagation of a flare-produced shock wave through the corona and interplanetary space, and simple models of this propagation have been based on analytic (e.g., Parker 1961, 1963; Simon and Axford 1966) or numerical (see reviews by Hundhausen 1972b and by Dryer 1974, 1975) solutions of the fluid equations. Ground-based K-coronameter observations (Hansen et al. 1974) showed that disturbances in the white-light corona are often associated with large solar flares and eruptive prominences, but the sensitivity and regularity of Skylab white-light coronagraph observations permitted the detailed study of more subtle mass ejections, so-called coronal transients. The resulting observational picture of coronal transients and their association with solar activity have been reviewed by Munro et al. (1979), Rust et al. (1979), and MacQueen (1980). Theoretical models of time-dependent coronal flow have been developed and applied to coronal transients by several workers (e.g., Anzer 1978; Mouschovias and Poland 1978; Steinolfson et al. 1978, 1981; Dryer et al. 1979; Pneuman 1980). Such numerical models, with their specific descriptions of the time and spatial variation of all the gas, could in principle be incorporated into the time-dependent ionization state calculations described below, but, as a first step in exploring time-dependent ionization effects, we shall eschew these detailed models and instead examine these effects in the context of a simpler shock model of the time-dependent coronal flow.

The shock model we shall use here is based on a simple kinematic description of the flow (see Owocki 1982), but it's properties simulate those of many gasdynamic shock solutions (e.g., Rogers 1956; Parker 1961, 1963; Simon and Axford 1966) that were derived for more idealized circumstances than we shall consider here. Despite its simplicity, this kinematic shock model will serve to illustrate how a Lagrangian approach of following the evolution of individual fluid parcels can simplify the numerical calculation of the ionization state in a time-varying coronal outflow. Because of the idealized nature of this model, the results of these calculations are inappropriate for detailed comparison with specific interplanetary charge state measurements, but they do clearly illustrate several interesting aspects of how a coronal shock wave affects the solar wind ionization state. Hence they provide a firm basis for the physical understanding of future calculations that employ more complicated hydrodynamic models of time-dependent coronal flow. In particular, our results strongly suggest that the effect of a strong coronal shock wave on the solar wind ionization state will be very limited, both in the magnitude of the change in ionization and in the time over which such changes will be seen.

II. THE IONIZATION STATE IN A TIME-DEPENDENT FLOW

Consider a time-dependent coronal ion outflow in which the various ionization stages i of a given element s are constantly undergoing ionization and recombination through interaction with electrons e. We write the conservation equation for each ionization stage (i = 0 to Z) as

\[ \frac{\partial n_i}{\partial t} + \nabla \cdot (n_i u) = n_s [n_{i-1} C_{i-1} - n_i (C_i + R_i) + n_{i+1} R_{i+1}] , \]  

where n and u refer to particle number density and bulk flow velocity, and the ionization and recombination rate coefficients \( C_i(T_e) \) and \( R_i(T_e) \) (cm\(^3\) s\(^{-1}\)) are functions of the electron temperature \( T_e \) (for the assumed Maxwellian electron velocity distribution) but not of density (Billings 1966; Allen and Dupree 1969). Assuming that the flow tubes of all stages are oriented along the radial coordinate r, we use the overall conservation of species s to describe changes in fractional abundance of stage i, \( y_i = n_i/n_s \), relative to the overall species number \( n_s = \sum n_i \),

\[ \frac{\partial y_i}{\partial t} + u \frac{\partial y_i}{\partial r} + (y_i - f_i) \frac{1}{n_s} \frac{\partial n_s}{\partial t} = n_s [y_{i-1} C_{i-1} - y_i (C_i + R_i) + y_{i+1} R_{i+1}] . \]

where \( u \equiv \sum y_i u_i \) is the mean species flow speed, and \( f_i \equiv n_i u_i/n_s u_s \) is the relative flux for stage i. In Paper I, we examined in detail the freezing-in of the ionization state for the case in which the coronal ion outflow is steady (\( \partial \phi/\partial t = 0 \)), but possibly not at the same speed for all ion stages (\( u_i \neq u_0 \)). In this paper, we investigate the ionization state effects of time variations associated with an outward-propagating shock, but we assume for simplicity that ions of all stages flow uniformly at the proton speed, \( u_0 = u = u \) (see § III for a brief discussion of the effects of unequal speeds in this model). With this assumption, there is no net flux of ions into or out of a fluid parcel that flows at the speed \( u_0 \), and so the ionization state of each parcel is independent of conditions in neighboring parcels. Computationally, equations (2) simplify so that all ionization state changes can be described in terms of a total derivative with respect to a Lagrangian coordinate \( r_L \),

\[ \frac{D}{D_L} y_i = \frac{\partial y_i}{\partial t} + \frac{\partial y_i}{\partial r} + \frac{\partial y_i}{\partial r} \frac{\partial r}{\partial L} \]

\[ = \frac{n_s}{u} [y_{i-1} C_{i-1} - y_i (C_i + R_i) + y_{i+1} R_{i+1}] . \]

Given the flow speed \( u \), electron density \( n_e \), and electron temperature \( T_e \) as functions of the Lagrangian coordinate...
Fluid parcel to obtain the ionization state evolution in \( r_L \). Reconstruction of the ionization state time variation at a fixed Eulerian space coordinate \( r \) (e.g., at \( r = 1 \) AU) then follows readily from the known ionization state of many fluid parcels flowing past the fixed coordinate at the known speed \( u \).

We have developed (see Owocki 1982) a kinematic description of strong coronal shocks from which we obtain, as required for calculation of the ionization state, the Lagrangian evolution of velocity, density, and temperature. We consider here only the special case in which the shock speed \( V \) is constant, and the postshock flow is neither compressive nor expensive. In this simple shock model, the velocity, density, and temperature of a fluid parcel shocked at \( r_L = R_1 \) change suddenly by an amount set from the strong shock jump conditions. Before being shocked (\( r_L < R_1 \)), the velocity, density, and temperature in the fluid parcel are given by an ambient flow model (chosen to approximate the expected variations in the “quiet” coronal expansion) in which, for \( r_L < R_1 \),

\[
\begin{align*}
  u_a(r_L) &= 0.7 \left( \frac{r_L}{R_\odot} \right)^3 \text{ km s}^{-1}, \\
  n_a(r_L) &= 2 \times 10^6 \left( \frac{r_L}{R_\odot} \right)^{-5} \text{ cm}^{-3}, \\
  T_a(r_L) &= 2 \times 10^6 \left( \frac{r_L}{R_\odot} \right)^{-2/7} \text{ K}.
\end{align*}
\]

After the shock (\( r_L > R_1 \)), the velocity is constant, the density declines with the outward spherical expansion, and the temperature excess above the ambient value declines adiabatically, for \( r_L > R_1 \):

\[
\begin{align*}
  u(r_L) &= \frac{3V}{4}, \\
  n(r_L) &= 4n_a(R_1) \left( \frac{r_L}{R_1} \right)^{-2}, \\
  T(r_L) &= T_a(r_L) + \Delta T_1 \left( \frac{r_L}{R_1} \right)^{-4/3}.
\end{align*}
\]

Here \( \Delta T_1 \equiv m_p \Delta u^2 / 6k \) is the adiabatic temperature jump appropriate for a velocity change \( \Delta u \equiv u(R_1) - u_a(R_1) \).

a) Oxygen Ionization State in Forward Shocks

Figure 1 shows the time variation of the oxygen ionization ratio temperature \( T_{e>7} \) (dashed curves) and oxygen ionization ratio temperature \( T_{e>7} \) (solid curves) versus Lagrangian radius \( r_L \) for the ambient, unshocked fluid flow and for three fluid parcels that are shocked, respectively, at \( R_1 = 1, 1.5, \) and \( 2 R_\odot \). The ionization ratio temperature is defined as the electron temperature that, in ionization equilibrium, would yield a given abundance ratio of, e.g., \( O^+6 \) versus \( O^+7 \); see Owocki 1982). Note that fluid parcels shocked at greater radii show progressively weaker ionization ratio temperature responses to the shock, but the net gain in the asymptotic, frozen-in, radio temperature is highest for the parcel shocked at the intermediate height \( R_1 = 1.5 R_\odot \). The parcel shocked at \( R_1 = 1 R_\odot \) initially shows a stronger jump in ionization ratio temperature, but it then continues to follow the local electron temperature as the parcel adiabatically cools. It thus freezes at a ratio temperature \( (1.8 \times 10^6 \text{ K}) \) enhanced only slightly above the value for the ambient flow \( (1.6 \times 10^6 \text{ K}) \).

On the other hand, the ionization state in the parcel with \( R_1 = 2 R_\odot \), being nearly frozen-in when shocked, does not follow this adiabatic cooling; but neither is its initial jump in ratio temperature very great, and so its frozen-in ratio temperature \( (1.8 \times 10^6 \text{ K}) \) is also only slightly enhanced above that of the ambient flow. The parcel shocked at \( R_1 = 1.5 R_\odot \) is intermediate between the frozen-in, small-jump case and the equilibrium, adiabatic-cooling case, and thus it shows the greatest frozen-in ratio temperature \( (2.1 \times 10^6 \text{ K}) \). Even this frozen-in ratio temperature does not, however, accurately reflect the magnitude of the assumed shock-associated temperature jump near the coronal freezing-in radius. This results from the tendency of the ionization state to freeze gradually, and thus to average out sharp temporal or spatial variations in coronal temperature. Figure 2 shows the time variation of frozen-in oxygen ionization ratio temperature \( T_{e>7} \) \( (r = 1 \text{ AU}) \) that results at \( 1 \text{ AU} \) from coronal shocks with various shock speeds \( V \). The abscissa gives the time \( \Delta t \) for passage of a coronally shocked fluid parcel relative to the time for passage of a parcel shocked at \( R_1 = 10 R_\odot \). All such fluid parcels trail by several hours the interplanetary passage of the shock itself. The dot that terminates each curve represents the time for passage of the parcel shocked at the coronal base; i.e., with \( R_1 = 1 R_\odot \). Because we have not included here any model of the driver gas, these shock calculations give no information on the ionization state after this time. (For flare-associated disturbances, this driver gas may be flare-heated plasma that itself has a very high degree of ionization.) The calculations do suggest, however, that several hours after the passage of a flare-associated...
interplanetary shock, and shortly before arrival of the flare-heated driver gas that caused the shock, the oxygen ionization temperature should show a brief, mild increase. The magnitude of this increase should, however, be much less than the shock associated jump in coronal electron temperature, and it should only last for a few times 10 minutes. Such a change in the oxygen ionization state would be too short-lived to be resolved by current detectors on interplanetary spacecraft.

b) Iron Ionization State in Forward Shocks

Because of the multistage nature of the iron ionization balance, the interpretation of its time variation is more subtle than for the oxygen case. Nonetheless, it can be understood through a combination of the simpler two-stage oxygen time-dependent results discussed above and previous steady state calculations of the multistage balance of iron. The various iron ionization/recombination exchanges can have differing response times to changes in conditions, and this leads in steady-flow cases to a "differential freezing" of the various iron ionization stages $Fe^{+12} \leftrightarrow Fe^{+8}$ over a range of heliocentric radii from $r \approx 3 R_\odot$ to $r \approx 4 R_\odot$ in the ambient flow (see Paper I). Similarly, the response to the sudden jump in temperature associated with the shock will also vary with ionization stage.

We have calculated the Lagrangian evolution of ratio temperature $T_{\text{Fe}^{i+1}/\text{Fe}^{i+2}}$ for the exchanges among the most abundant iron stages $i = 9-12$ in fluid parcels shocked at various radii $R_1$ in this shock model. For parcels shocked at the relatively low, dense level $R_1 < r_f$ (where $r_f \approx 4 R_\odot$ is the iron ionization state freezing level), each of the ratio temperatures $T_{\text{Fe}^{i+1}/\text{Fe}^{i+2}}$ shows a sharp response to the jump in electron temperature, but the higher stage exchanges (e.g., $Fe^{+12} \leftrightarrow Fe^{+13}$) then fail to follow the subsequent adiabatic cooling; the resulting asymptotic ratio temperatures thus increase with ionization stage. For the parcel shocked at the intermediate level $R_1 \approx r_f$, each of the exchanges has already begun to freeze-in according to the ambient conditions when the shock occurs, and thus, overall, the responses to the temperature jump are less pronounced. Nonetheless, what response there is is greatest for the lowest (and fastest) exchange $Fe^{+9} \leftrightarrow Fe^{+10}$, and so the asymptotic ionization ratio temperature is now larger for the lower ionization exchanges. Finally, in a parcel shocked at the still higher level $R_1 > r_f$, all of the exchanges have completely frozen-in, and so the shock has no effect on the ionization state. This parcel thus has asymptotic ratio temperatures that are the same as those in the differentially frozen, steady state flow.

These results are summarized in Figure 3, which shows the asymptotic ratio temperatures $T_{\text{Fe}^{i+1}/\text{Fe}^{i+2}}$ (r = 1 AU) as a function of the shock radius $R_1$ for various iron charge stages $i = 9-12$. For parcels shocked at large heliocentric radii, each ratio temperature approaches the appropriate differentially frozen-in value of the steady-flow case, whereas, for parcels shocked at intermediate radii, the lower ionization ratios actually have a higher frozen-in temperature because of their weaker response to the adiabatic cooling. For parcels shocked at still smaller radii, the slower exchanges among the higher stages result in their freezing at the enhanced temperature immediately behind the shock. The greater range in frozen-in ratio temperatures have relative to the steady state.
case results from the fact that the density falloff with \( r_L^{-2} \) is much slower, whereas the temperature decline induced by the adiabatic cooling is much faster; hence the various exchanges freeze over a greater range in Lagrangian radius, throughout which the electron temperature change is also greater. In fact, in the parcel with \( R_L = R_0 \), the freezing of the exchange \( \text{Fe}^{+9} \leftrightarrow \text{Fe}^{+10} \) does not occur until \( r_L \approx 10 R_0 \), and at this height, both the shock-heated and ambient components of the temperature have decreased so much that the frozen-in temperature is actually smaller than for an unshocked parcel in the ambient flow.

Finally, Figure 3 also shows the time variation in the iron ionization ratio temperature that a spacecraft at 1 AU would observe if this reference shock model were indeed an accurate representation of conditions in the low corona. The upper horizontal axis gives the time (increasing to the left) in minutes since the time \( t_s \) for passage of the shock front itself. As with the time variation of the oxygen ionization state (see above), the iron ionization temperature variation occurs over time scales of a few times 10 minutes.

III. DISCUSSION

We reiterate that the above time-dependent ionization state calculations are only meant to be illustrative and are too idealized to be used for matching observed interplanetary ionization state changes with inferred intrinsic time variations in the solar corona. Our shock model is strictly a kinematic description, not a solution of the time-dependent dynamical equations, and it is based on the assumption that the shock is well formed and strong right from the coronal base. Furthermore, we have ignored the effects of thermal conduction in smoothing the electron temperature jump across the shock, and so the assumed magnitude of this jump is probably an overestimate of what occurs in an actual strong coronal shock wave.

In spite of these shortcomings in the model, the calculations presented here do provide a sound basis for understanding physically how a coronal shock wave can affect the solar wind ionization state. In particular, they indicate that, in the sudden transition between the otherwise steady flows, the period when true time-dependent effects are important is generally limited to a time of about 10 minutes for transit of the disturbance through the lower corona, where the ionization state has not yet frozen-in. In addition, because of the tendency of the coronal ionization state to freeze gradually, and so average out rapid temporal or spatial variations, any sharp peak in coronal electron temperature associated with such disturbance will cause only a greatly diminished peak in the frozen-in ionization temperatures of the resulting solar wind disturbance. This implies a breakdown in the usual association of the frozen-in ionization state with the temperature at a discrete height. Furthermore, because the coronal temperature jumps assumed here are likely to be overestimates, these calculations represent upper limits to the expected effect of a coronal shock wave on the solar wind ionization state.

We have examined (Owocki 1982) the sensitivity of these results to some of the simplifying assumptions about the nature of the shock flow. We find qualitatively similar results in models with compressive or expansive flow behind the shock and in models in which the shock is accelerating or decelerating. We also find that a reverse shock (Hundhausen 1972b; Simon and Axford 1966), if it exists in the corona (see Steinolfson and Nakagawa 1976 for arguments why it might not), can have no effect on the solar wind ionization state because the ionization state is already frozen in the high-speed, low-density coronal flow into which such a shock must propagate. We further find (Owocki and Scudder 1982, 1983) that a non-Maxwellian electron distribution, such as might be expected in the neighborhood of a strong coronal shock, can significantly alter the relationship between coronal electron temperature and degree of ionization, particularly for oxygen.

Finally, because of electrostatic fields that should exist near a strong shock, ions with higher ratios of charge to mass are likely to be accelerated to greater speeds in the postshock flow. In Paper I we showed that such unequal ion flow in the steady state solar wind leads to an apparent enhancement in the frozen-in ionization ratio temperature. Similar effects of unequal ion flow speeds are to be expected in the shock models considered here, where the flow is also steady (i.e., time independent), except for the sudden changes at the shock boundary. In principle, these effects could further complicate the interpretation of the ionization state of solar wind plasma that has been shocked in the corona, but in practice, they are likely to be negligible. If ions crossing the shock are accelerated primarily by the electric field, then the energy they obtain should scale in proportion to their charge. This implies that the flow speeds of, e.g., \( O^{+7} \) and \( O^{+6} \) should differ only by about 8% (i.e., \( 7/6^{1/2} = 1.08 \)), which leads to errors in inferred ionization ratio temperature of only a few percent (see Paper I; also Owocki 1982).

IV. SUMMARY

In this paper, we have examined the degree to which intrinsic time variations at the base of the solar wind can influence the interplanetary ionization state. We have shown that, by using a Lagrangian approach of following individual fluid parcels, the methods used previously for calculating the ionization state in steady flows can be straightforwardly extended to the time-varying case. Given the time and spatial variations in density, velocity, and temperature, this approach is applicable whenever all charge stages of a given species have a common flow speed at a given position and time.

Calculations using a simple kinematic shock model showed that only fluid parcels shocked at or below the ambient freezing-in radius had their ionization state modified by the shock. In parcels shocked well inside this radius, the degree of ionization initially
increased sharply because of heating at the shock, but it then declined because of adiabatic cooling with the outward expansion; the asymptotic degree of ionization for such parcels can actually be lower than for the unshocked ambient flow. Parcels shocked near the freezing-in radius showed less of an initial response to the heating, but they were already frozen-in during the cooling phase and thus had a moderately enhanced asymptotic degree of ionization. For the enhanced, supersonic flow that drives a forward shock into an ambient slower expansion, the ionization state is always frozen, and so any reverse shock that propagates back through this driver gas can have little effect on its ionization state. Time-dependent ionization effects for the transition between two steady flows are thus likely to be limited to a narrow range of gas parcels which, having been struck by the forward propagating shock in the very low corona, pass a fixed interplanetary observer in an interval of a few times 10 minutes. Furthermore, the amplitude of any rise in interplanetary ionization temperature associated with this coronal shock is likely to be considerably smaller than the jump in electron temperature that actually occurs in the corona.

In summary, we conclude that a strong coronal shock wave can affect the solar wind ionization state, but that these effects are very limited, both in the magnitude of the increase in ionization and in the time over which such changes will be seen.

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