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AN OSCILLATORY INSTABILITY OF INTERSTELLAR MEDIUM RADIATIVE SHOCK WAVES

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ABSTRACT

Observations of the radiative shock waves produced during the late stages of supernova remnant evolution cannot be understood in the context of steady state shock models. As a result, several more complicated scenarios have been suggested. For example, it has been proposed that several shocks are producing the emission or that one shock, which is in the process of making the transition between the adiabatic and the radiative phases of its evolution, produces the emission. In this paper, we suggest another explanation. We propose that supernova remnant shock waves are subject to an oscillatory instability. By an oscillatory instability, we mean one where the postshock cooling region periodically varies in size on a time scale determined by the postshock plasma cooling time. An oscillatory instability may be able to produce the types of behavior exhibited by supernova remnant radiative shocks in a natural way.

INTRODUCTION

A radiative shock wave is a shock in which the cooling time scale of the plasma downstream of the shock transition is less than the characteristic flow time of the postshock plasma. The thickness of the transition region is on the order of the particle mean free path, λ_p, while the thickness of the cooling region, λ_{cool}, is determined by the postshock velocity and cooling time of the plasma. Such a shock is composed of three regions: (1) a precursor in which the inflowing plasma can be heated, ionized, or dissociated by an energy flux from behind the shock; (2) a transition region in which the bulk kinetic energy of the incoming plasma is converted into thermal motions; and (3) a more extended region in which the shock-heated plasma radiates away its internal energy relaxing to its final state. In general, $\lambda_p \ll \lambda_{cool}$ and the ionization, dissociation, or heating length scale of the precursor. Because of this, most models of radiative shock waves take the transition region to be a discontinuity and only model the cooling region and precursor in detail.

Radiative shock waves arise in a wide variety of interesting astrophysical situations. For instance: (1) they can occur in X-ray binary systems[1-5]. In these cases, plasma flows from the "normal" star in the binary system to its companion, a compact object (e.g., a white dwarf or neutron star). If the accreting plasma approaches the compact object radially or approximately radially, it forms a stand-off shock and then cools as it settles onto the surface of the object. (2) Radiative shocks can occur during the late stages of supernova remnant evolution[3-10].

Immediately after the initial supernova outburst,[1] the ejecta from the outburst expand with a velocity of ~ 10^4 km s^{-1}; sweeping up the surrounding interstellar medium. When the amount of swept up mass is small, the ejecta move at constant velocity. This "free" expansion continues until the ejecta have interacted with an amount of mass approximately equal to their own, after which time they are strongly decelerated and assume a structure which is quite nicely modeled as a Sedov blast wave. The blast wave phase lasts until the postshock cooling time scale becomes less than the postshock flow time scale. This occurs around the time that the shock velocity has dropped to two hundred kilometers per second. The cooling leads to the formation of a dense shell near the outer edge of the remnant which, driven by the hot plasma in the interior of the remnant, acts like a piston driving a radiative shock wave into the interstellar medium. (3) Radiative shock waves occur during the interaction of stellar winds and the interstellar medium. If the shock velocities are sufficiently low, the plasma cooling time scale will be shorter than the flow time scale and radiative shocks will be produced. Examples of this are the Herbig-Haro phenomenon[14] and the late stages of the evolution of stellar wind blown bubbles[16].

In this work, we concentrate our remarks to the radiative shocks produced by supernova remnants, but our results also apply to the shocks produced by the interaction of stellar winds and the interstellar medium.

The structure and appearance of steady interstellar medium radiative shock waves have been the subjects of several extensive theoretical efforts in the last decade[10]. However, when the results of the calculations are compared to observations, the agreement is not always good. For example, the observations of the old supernova remnants, Vela and the Cygnus Loop, cannot be fit by unique steady state shock models. The observations require that time-dependent phenomena be present or that there be several shocks with a range of shock velocities present[12]. The resolution of this problem is not readily apparent. Because of this, it is of interest to consider effects which could lead to such scenarios. Instabilities of the postshock cooling regions of radiative shock waves are good candidates for such processes.

The stability properties of the cooling regions of radiative shock waves are incompletely understood. Two basic types of instabilities have been considered. There are thermal instabilities[2,9], that is, instabilities which occur at approximately constant pressure. Such instabilities tend to lead to "clumping" of the cooling plasma through the amplification of preshock density fluctuations. They mainly affect the observable features of radiative shock waves; they do not affect the shock dynamics. There are also "oscillatory" types of instabilities, in which cooling and dynamical processes both play major roles[4-8]. In oscillatory instabilities, the size of the cooling region varies in size with a characteristic oscillation period on the order of the postshock plasma cooling time scale. Whether the shock is unstable to oscillatory motions is determined by the form of the plasma cooling function. We consider oscillatory instabilities in this paper. There have not been any detailed calculations of time-dependent interstellar medium radiative shock waves and thus, there are no direct demonstrations that they are unstable to oscillatory motions. However, studies of the stability properties of radiative shock waves using power law cooling functions proportional to $\rho^2 T^\alpha$ [4] have suggested that interstellar medium shocks may be unstable.

The rest of this paper is organized as follows. In Section II, the qualitative nature of the instability is discussed and the results of the linear and nonlinear stability analyses are presented, and in Section III, interstellar medium shock waves are discussed in the context of oscillatory instabilities.

SHOCK STABILITY PROPERTIES

A. Qualitative Picture

The oscillatory instability of radiative shock waves can be understood by considering planar shock waves. Consider the situation where plasma flows from the $x = +\infty$ direction along the x-axis towards a stationary wall situated in the y-z plane at $x = 0$. The plasma has a velocity $-v_{in}$, density ρ_{in}, and pressure P_{in} ($=0$). This highly supersonic plasma forms a strong shock at a distance x_s from the wall and then cools as it settles onto the wall. The characteristic time scale of the shocked plasma is the postshock plasma cooling time, τ_{cool}, defined as the ratio of the internal energy of the postshock plasma to the emissivity of the postshock plasma. The distance x_s is of the order of the product of the absolute value of the postshock plasma velocity and τ_{cool}. Whether a perturbation of the position of the shock front (and therefore of the shock velocity) grows or damps depends upon the form of the plasma cooling function. To see this, consider a power law cooling function of the form $\Lambda_3 = \Lambda_0 \rho^\beta T^\alpha$, where Λ is the plasma emissivity in units of ergs cm^{-3} s^{-1}, Λ_0 is a constant, T is the temperature, and α and β are constants. Consider the fluid in a frame in which the shock velocity would be zero if it were in equilibrium, but allow for a small nonzero shock velocity, v_s. The cooling time scale and postshock velocity are then found to be

$$\tau_{cool} = \frac{\text{Internal Energy of the Plasma}}{\text{Plasma Emissivity}}$$

$$= \tau_0 \frac{(v_{in}+v_s)^{2(1-\alpha)}}{\rho_{in}^{\beta-1}} \qquad (1)$$

and

$$v_{post} = -\frac{v_{in} - 3v_s}{4} \tag{2}$$

Here $\tau_o = (9/8)\,(16k/3\mu m_o)^{\alpha}\, 4^{-\beta}\, \Lambda_o^{-1}$, μ is the mean molecular weight, m_o is the atomic mass unit, and v_{post} is the postshock velocity. Defining $\lambda_{cool} = 0.25|v_{post}|\,\tau_{cool}$ and assuming that $|v_s/v_{in}| << 1$, we have

$$\lambda_{cool} = \tau_o \frac{v_{in}^{3-2\alpha}}{4\rho_{in}^{\beta-1}}\left[1-(1+2\alpha)\frac{v_s}{v_{in}}\right]$$

$$= \lambda_s + \delta\lambda. \tag{3}$$

Here λ_s is the steady shock thickness, $\delta\lambda$ is the perturbation of the shock thickness. Equation (3) shows that if $\alpha \geq -1/2$, λ_{cool} is smaller than its equilibrium value if $v_s > 0$ (i.e., if the shock front is perturbed away from the wall), and is larger than its equilibrium value if $v_s < 0$ (i.e., if the shock front is perturbed towards the wall). Thus, one expects that the cooling region will be stable against small perturbations to the shock front position if $\alpha > -1/2$. However, because this estimate ignores the detailed structure of the cooling region, it does not yield the quantitatively correct value of the critical temperature exponent α or the dependence of the stability properties on the exponent of the density dependence β. It does indicate, however, the qualitative effect of varying the temperature exponent α on the stability of radiative shock waves, that is, for large values of α, radiative shock waves are expected to be stable against oscillatory motions.

B. Detailed Calculations

Linear and nonlinear studies of radiative shock waves with cooling functions $\Lambda = \Lambda_o \rho^{\beta} T^{\alpha}$ have been carried out. Values of β = 1 and 2, and values of α ranging from -2 to 2 have been considered. All calculations assumed that the electron and ion temperatures were equal, that viscosity and electron thermal conduction were negligible, and that geometrical effects were small. For interstellar medium shocks, these assumptions are usually justified, however, for radiative shocks produced by accretion onto compact objects, these assumptions break down in several situations[6,15]. The details of our linear calculations can be found in Refs. 4 and 5, and the details of our nonlinear calculations can be found in Refs. 5 and 6. In general, there is very good quantitative agreement between the linear and nonlinear analyses (however, see Ref. 6 for a discussion of the slight differences in the nonlinear calculations). Because of this, only the results of the linear analyses for the onset of instability in terms of the α value and the oscillation frequencies are presented.

Radiative shock waves are found to be capable of oscillating in several distinct modes, which are called, in order of increasing oscillation frequency, the fundamental (F), the first overtone (1O), the second overtone (2O), and so on. For $\beta = 2$ cooling functions, i.e., cooling functions where the loss processes are due to particle collisions, such as bremsstrahlung, collisionally excited line radiation, etc., the F, 1O, and 2O modes are stable for $\alpha \gtrsim 0.4$, 0.8, and 0.8, respectively. For $\beta = 1$ cooling functions, i. e., cooling functions where the loss processes are due to single particle processes such as Compton or cyclotron cooling, the F, 1O, and 2O modes are stable for $\alpha \gtrsim 0.05$, 0.14, and 0.34, respectively. For both types of cooling functions, the oscillation frequencies are ~ 0.3-0.4 (v_{in}/x_s) for the F mode, ~ 0.6-1.0 (v_{in}/x_s) for the 1O mode, and ~ 1.3-1.5 (v_{in}/x_s) for the 2O mode. Note that (v_{in}/x_s) is $\propto 1/\tau_{cool}$ showing that the oscillation periods are on the order of the postshock plasma cooling time scale.

In general: (1) the larger the value of α, i.e., the stronger the temperature dependence of the cooling function, the more stable the shocks are likely to be; and (2) the smaller the value of β, i.e., the weaker the density dependence of the cooling function, the more stable the shocks are likely to be.

Examples of the behavior of radiative shock waves in the nonlinear regime are presented in Figure 1. The the shock luminosity, L_s, as a function of time, is presented for $\beta = 2$ and $\alpha = 1$, 1/2, and 1/3 models. The linear analysis predicts that the F mode will be stable for $\alpha \gtrsim 0.4$, and that the 1O and 2O modes will be stable for $\alpha \gtrsim 0.8$. The nonlinear analysis is in good agreement with this prediction.

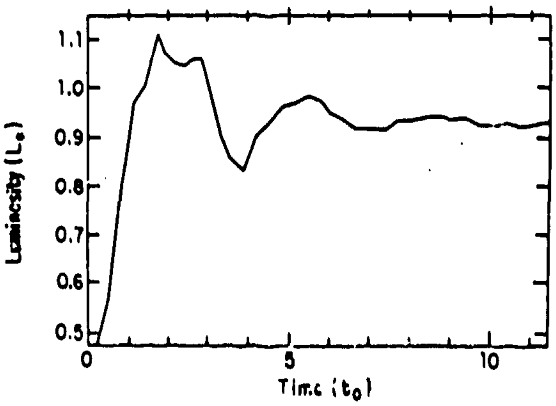

Figure 1a: the shock luminosity as a function of time for a power law cooling function of the form $\Lambda = \rho^2 T^1$. The luminosities are in units of the average luminosity and the times are in units of $2\pi(x_s/v_{in})$.

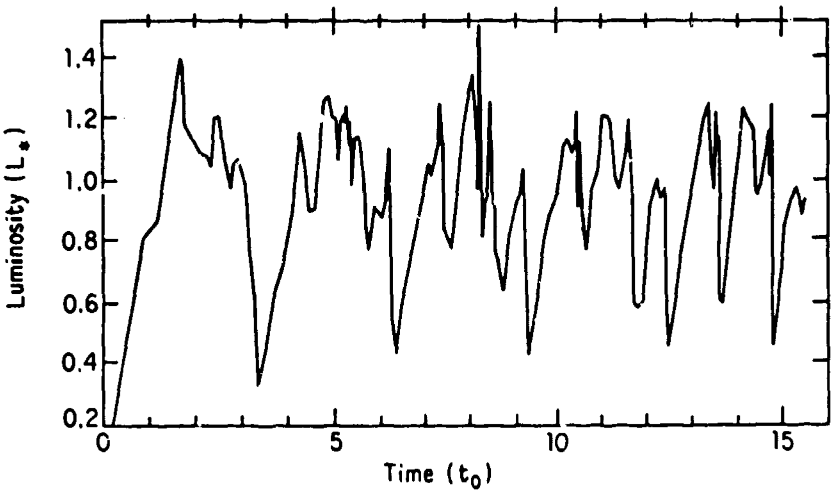

Figure 1b: Same as Figure 1a, except that the cooling function has the form $\Lambda \propto \rho^2 T^{1/2}$.

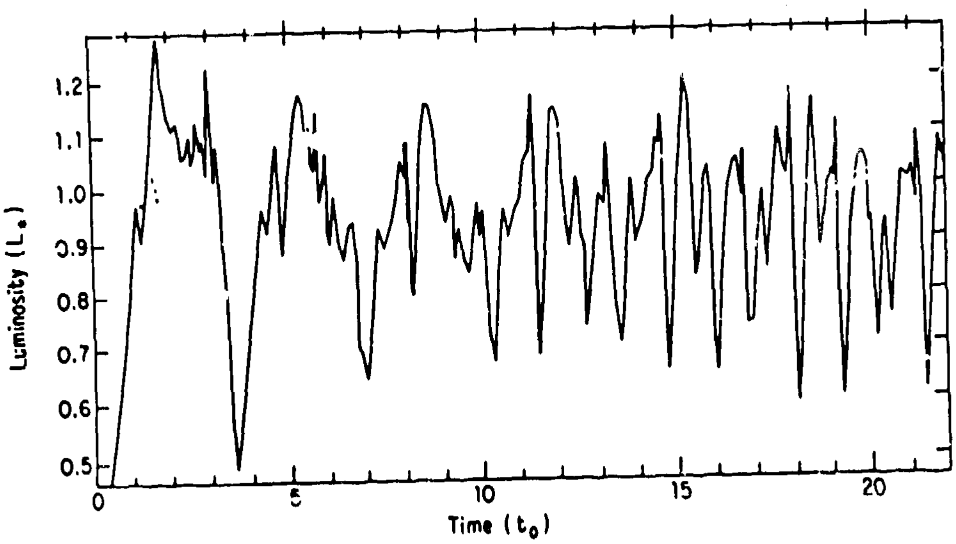

Figure 1c: Same as Figure 1a, except that the cooling function has the form $\Lambda \propto \rho^2 T^{1/3}$.

INTERSTELLAR MEDIUM RADIATIVE SHOCK WAVES

The oscillatory instability may occur in interstellar medium radiative shock waves even though there isn't a fixed surface onto which the plasma flows. In the interstellar medium, radiative shocks are driven by a cold, dense shell of plasma whose motion can be assumed to be constant as the cooling time of the plasma is short compared to the time over which the layer evolves. This is the assumption normally made in the study of interstellar medium shock waves and is equivalent to the statement that the column density of the swept up matter is large compared to the column density through the cooling region. The application of the oscillatory stability results to interstellar medium shocks requires that the perturbed velocity go to zero at the swept up layer. However, it is not *a priori* obvious that the pressure perturbation also goes to zero at the swept up layer. The effect of requiring the pressure perturbation to go to zero at the dense layer, rather than the velocity perturbation, was checked by a linear analysis. The change in the boundary condition had no effect on the onset of instability or the oscillation frequencies.

The cooling losses of interstellar plasma are primarily due to particle collisions and thus the $\beta = 2$ results are the relevant ones. In general, however, interstellar medium cooling functions are not a single power law in T and so the results of the stability analyses just presented are not strictly applicable[11]. However, because most of the radiated energy comes from plasma at temperatures close to that found near the shock wave, only requiring that the cooling function be a power law for temperatures around the shock temperature may be sufficient. Using the equilibrium interstellar medium cooling function[13], the emissivity can be approximated as $\Lambda \propto \rho^2 T^{0.55}$ for temperatures in the range 10^5 to 4×10^7 K. Thus, for these shock temperatures, we expect that interstellar medium radiative shock waves will be unstable. However, because nonequilibrium ionization effects substantially alter the cooling function[11], this result is only suggestive. Detailed time-dependent numerical hydrodynamic calculations are needed to verify this claim.

Comparisons of the spectral observations of supernova remnants with shock wave emission models generally yield shock velocities in the range 90-140 km s^{-1}[12]. The oscillatory instability may occur in this regime, but the time scale is too long to observe time variations. The cooling time scale for the interstellar medium case is on the order of hundreds of years. Thus, the instability should thus manifest itself as deviations of the observed spectra from those predicted by the steady shock models. There is a great deal of evidence for such effects, particularly when UV data are combined with optical data[12]. Other evidence is the high [O III]/Hβ line ratio observed in parts of many supernova remnants. Raymond *et al.*[12] argue for nonsteady emission and consider three possible explanations. The first is the thermal instability of McCray *et al.*[9]. They consider this an unlikely explanation because the steady models in the 2×10^4 to

2×10^5 K range reproduce the observed line intensities and because the spectrum appears uniform over the IUE aperture. The other two explanations are that the shock wave is just in the process of making the transition from an adiabatic to a radiative shock wave, either where it comes into contact with a dense cloud or a homogeneous medium. We believe that this special situation is unlikely because the evidence for nonsteady behavior is so widespread.

Thus, we are led to propose that the oscillatory instability is the cause of the apparent nonsteady emission[4]. If interstellar medium shocks oscillate in low order modes, it is possible that their structures in different temperature ranges will reflect different shock velocities and thus lead to spectra which appear to contain contributions from steady state shocks of several shock velocities. More detailed calculations are needed to verify this claim.

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