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Cosmic rays and radiative instabilities

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Abstract. In the absence of magnetic fields and cosmic rays, radiative cooling laws with a range of dependences on temperature affect the stability of interstellar gas. For about four and a half decades, astrophysicists have recognised the importance of the thermal instablity for the formation of clouds in the interstellar medium. Even in the past several years, many papers have concerned the role of the thermal instability in the production of molecular clouds. About three and a half decades ago, astrophysicists investigating radiative shocks noticed that for many cooling laws such shocks are unstable. Attempts to address the effects of cosmic rays on the stablity of radiative media that are initially uniform or that have just passed through shocks have been made. The simplest approach to such studies involves the assumption that the cosmic rays behave as a fluid. Work based on such an approach is described. Cosmic rays have no effect on the stability of initially uniform, static media with respect to isobaric perturbations, though they do affect the stability of such media with respect to isentropic perturbations. The effect of cosmic rays on the stability of radiative shocked media depends greatly on the efficiency of the conversion of energy in accelerated cosmic rays into thermal energy in the thermalized fluid. If that efficiency is low, radiative cooling makes weak shocks propagating into upstream media with low cosmic-ray pressures more likely to be cosmic-ray dominated than adiabatic shocks of comparable strength. The cosmic-ray dominated shocks do not display radiative overstability. Highly efficient conversion of cosmic-ray energy into thermal energy leads shocked media to behave as they do when cosmic rays are absent.

Key words. shock waves – ISM: kinematics and dynamics – ISM: cosmic rays – hydrodynamics – instabilities – ISM: clouds

1. Introduction

After briefly reviewing the thermal instability of a non-magnetized, static, uniform fluid containing no cosmic rays, we mention the importance of the thermal instability in recent models of molecular cloud formation and then consider the effects of cosmic rays on the instability of a medium like that described above. Then

Send offprint requests to: T. W. Hartquist we describe work on the radiative instability of non-magnetized shocked fluids containing no cosmic rays, before addressing the effects of cosmic rays on such media.

2. Thermal stability of a uniform fluid with no cosmic rays

In a static equilibrium fluid containing no magnetic field or cosmic rays

$$\rho\mathcal{L}(\rho, T) = 0 \tag{1}$$

ρ and T are the mass density and temperature, respectively, and $\rho\mathcal{L}$ is the net energy loss per unit volume per unit time. In order to write the criteria for thermal stability (Field 1965) of such a state, we introduce some notation.

$$a \equiv \left(\frac{\gamma_g P_{g0}}{\rho_0}\right)^{\frac{1}{2}} \tag{2}$$

$$k_T \equiv \frac{\mu(\gamma_g - 1)}{Ra} \left.\frac{\partial\mathcal{L}}{\partial T}\right|_{T=T_0} \tag{3}$$

$$k_\rho \equiv \frac{\mu(\gamma_g - 1)\rho_0}{RaT_0} \left.\frac{\partial\mathcal{L}}{\partial\rho}\right|_{\rho=\rho_0} \tag{4}$$

a is the adiabatic sound speed, γ_g is 5/3 for a fully ionized gas, R is the gas constant, μ is the mean mass per particle, and the subscript zero indicates that the value of the quantity is that appropriate for the equilibrium state.

Such a medium is stable with respect to isobaric perturbations if

$$k_T - k_\rho > 0 \tag{5}$$

It is stable with respect to isentropic perturbations if

$$k_T - \Delta > 0 \tag{6}$$

$$\Delta \equiv \frac{k_T - k_\rho}{\gamma_g} \tag{7}$$

Often $\mathcal{L}$ can be written as $\Lambda(T)n - \Gamma$, where n is the number density of nuclei, Λ depends on only the temperature, and Γ is a constant. When this is appropriate, stability with respect to isobaric perturbations requires that $\alpha \equiv (T/\Lambda)(d\Lambda/dT)$ exceeds unity and stability with respect to isentropic perturbations requires that α exceeds -1.5.

3. The significance of thermal instability for cloud formation

For conditions approaching the so-called typical interstellar conditions, the function $n(P_g)$, satisfying $\mathcal{L}(n, P_g) = 0$, is single-valued for low values of P_g (e.g., Wolfire et al. 1995); the corresponding value of T is of the order of 10^4K. For a range of values of P_g within a factor of a few of 4×10^{-13} erg cm^{-3}, n is treble-valued. The state corresponding to the intermediate solution is thermally unstable, and the temperatures of the other two states are of the order of 10^4K and 10^2K, respectively. For high values of P_g, n is single-valued, and the corresponding value of T is of the order of 10^2K.

The structure of the $n(P_g)$ curve implies that a shock of fairly modest strength, encountering a medium that initially is cloudless and has P_g only a bit below the typical interstellar value, can increase the pressure enough that some of the gas becomes thermally unstable and forms clouds. Such pictures for the formation of molecular clouds have been explored for over a decade. At first, much work was focussed on non-magnetic models. The many recent models of collisions of magnetized streams of gas that trigger cloud formation due to thermal instability include those of Hennebelle et al. (2008) and Heitsch et al. (2009).

Models of shocks interacting with radiative, magnetized clumps of gas leading to the formation of dense clouds include the two-dimensional models of Lim et al. (2005) and Van Loo et al. (2007) and the three-dimensional model of Van Loo et al. (2010). The finite extent of the obstacles alleviates the over efficiency of star formation associated with the colliding stream models. However, collisions between clumps of finite extent may trigger cloud and star formation at least as frequently as supernova remnant or superbubble shocks encountering clumps. In any case, Van Loo et al. (2007) found considerable similarities between the structure of their model and the observed structure of W3. They also illuminated the different roles of the fast-mode and slow-mode shocks. A fast-mode shock propagates into the clump first, and behind it radiative losses create magnetically dominated regions. The following slow-mode shock compresses the gas and creates a dense shell in which the magnetic pressure is not much larger than the thermal pressure. Van Loo and his collaborators have shown that the triggering shock must be of moderate strength. Shocks with Alfvénic Mach numbers greatly exceeding 2.5 cause the clumps that they hit to evolve on too short of a timescale compared to the lifetimes of observed molecular clouds. Significantly weaker shocks do not lead to the creation of magnetically dominated regions.

4. A uniform, static medium with cosmic rays

Using a two-fluid approach like that employed by McKenzie & Völk (1982), Wagner et al. (2005) examined the stability of a perturbed uniform radiative medium having a uniform cosmic ray pressure. Shadmehri (2009) performed a similar analysis but also included a large-scale magnetic field and thermal conduction, which we neglect here. Additional relevant parameters include:

$$z \equiv \frac{\omega}{ak} \tag{8}$$

$$k_c \equiv \frac{a}{\chi} \tag{9}$$

$$\phi \equiv \frac{\gamma_c P_{c0}}{\gamma_g P_{g0}}. \tag{10}$$

ω, k, P_c, γ_c, and χ are the angular frequency of the perturbation, its wavenumber, the cosmic ray pressure, the adiabatic index of the cosmic ray fluid, and the cosmic ray diffusion coefficient, respectively.

The dispersion relation is

$$G(z) \equiv z^4 - iz^3\left(\frac{k}{k_c} + \frac{k_T}{k}\right) - z^2\left(\frac{k_T}{k_c} + \phi + 1\right) + iz\left(\frac{k_T}{k}\phi + \frac{k}{k_c} + \frac{k_T - k_\rho}{\gamma_g k}\right) + \frac{k_T - k_\rho}{\gamma_g k_c} = 0. \tag{11}$$

Stability requires that

$$\frac{k_T - k_\rho}{\gamma_g k_c} > 0 \tag{12}$$

as well as

$$\frac{k_T\phi + \frac{k_T - k_\rho}{\gamma_g} + \frac{k^2}{k_c}}{k_T + \frac{k^2}{k_c}} > \frac{1}{2}\left(\phi + \frac{k_T}{k_c} + 1\right) - \sqrt{\frac{1}{4}\left(\phi + \frac{k_T}{k_c} + 1\right)^2 - \frac{k_T - k_\rho}{\gamma_g k_c}} \tag{13}$$

and

$$\frac{k_T\phi + \frac{k_T - k_\rho}{\gamma_g} + \frac{k^2}{k_c}}{k_T + \frac{k^2}{k_c}} < \frac{1}{2}\left(\phi + \frac{k_T}{k_c} + 1\right) + \sqrt{\frac{1}{4}\left(\phi + \frac{k_T}{k_c} + 1\right)^2 - \frac{k_T - k_\rho}{\gamma_g k_c}}. \tag{14}$$

The first of these conditions implies that cosmic rays do not influence the thermal stability of a medium with respect to isobaric perturbations, though cosmic rays can affect the growth rate. The other conditions imply that cosmic rays do influence the thermal stability of a medium with respect to isentropic perturbations. The final two conditions are sufficiently complicated that examination of them in various limits is desirable. For instance, in the limit of very large ϕ and very large k_c, the growth of insentropic perturbations is negligible for all cooling functions. ϕ is not large throughout most of the local interstellar medium. However, the limit is relevant for cosmic-ray dominated shocks in supernova remnants.

5. Radiative shocks without cosmic rays

Falle (1975) and McCray et al. (1975) first showed that radiative shocks are in some cases unstable. Later Falle (1981) and Langer et al. (1981) discovered that under some circumstances they oscillate due to global overstability. Numerical work (e.g., Imamura et al. 1984; Strickland & Blondin 1995) showed that high Mach number shocks are overstable if $\alpha < 0.4$, in good agreement with the results of a linear stability ananlysis (Chevalier & Imamura 1984). Pittard et al. (2005) showed that the range of values of α for which radiative shocks are overstable depends on the ratio of the far downstream temperature to the far upstream temperture and the Mach number. (A value of the ratio differing from unity will result if the equilibrium temperature is a function of pressure.) For a fixed value of the temperature ratio of unity, the maximum value of α for which a shock is overstable decreases with decreasing Mach number.

Though the purely hydrodynamic models indicate that many radiative shocks in supernova remnants should be non-steady, steady shock models have typically been used with reasonable success in the analysis of observations of radiative supernova remnant shocks (e.g., Raymond et al. 2001).

6. Radiative shocks with cosmic rays

Wagner et al. (2006) adopted the two-fluid approach to constructing plane-parallel models of radiative shocks to determine the effects of cosmic rays on the development of the overstability. They assumed that the magnetic field is dynamically unimportant and that the only energy transfer from the cosmic ray fluid to the thermal fluid occurs due to the inclusion of the derivative of the cosmic ray pressure in the equation governing the momentum of the thermal fluid. In most models they ignored the effects of cosmic rays long enough for the overstability to develop as it would in a single radiative thermal fluid. Then an initially uniform cosmic ray pressure was introduced. The distant upstream value of this pressure was maintained at a constant value, and the evolution of the pressure elsewhere was governed by the appropriate moment of the the transport equation.

Wagner et al. (2006) found that, no matter what the distant upstream cosmic ray pressure is, the downstream flow behind a shock with a Mach number, $M \equiv V_s/a$ where V_s is the shock speed, of 3 or more is cosmic-ray dominated. Cosmic-ray dominated shocks are stable and steady. Their model implies that shocks that are radiative rather than adiabatic are cosmic-ray dominated for a wider range of Mach number, preshock cosmic ray pressure parameter space. For sufficiently large ratios of the diffusion length to the cooling length, the cosmic-ray dominated shocks are nearly isothermal with structures similar to those given by analytic solutions for cosmic-ray dominated, strictly isothermal flows.

The 2006 model is not realistic. It implies that the postshock to preshock density ratio is close to 7 in shocks with M of 3 or more, a result that is not consistent with previous efforts to interpret observations of radiative supernova remnant shocks (e.g., Raymond et al. 2001).

Greater compression factors can be obtained for models in which sufficient cosmic ray energy is transformed into thermal energy of the thermal fluid. One mechanism causing the required transformation is the acoustic instability that Drury & Falle (1986) found to occur in shocks when χ/a exceeds the absolute value of $\gamma_c P_c(\partial P_c/\partial x)^{-1}$, where the x-axis is parallel to the shock velocity. To account for heating due to the acoustic instability, Wagner et al. (2007) included a source term in the thermal fluid energy equation. When the acoustic instability condition is not met, the term is zero. When the condition is strongly satisfied, the term is approximately $3P_g/2\tau$ for $\gamma_g = 5/3$, where τ is a specified time constant, which is taken to be a free parameter but can be constrained by appropriate observations as it was in work mentioned in the next section. When the acoustic instability condition is very weakly satisfied, the term approaches 0. The full expression for the term is given in Eq. (8) in the paper by Wagner et al. (2007).

Those authors showed that if $V_s\tau$ is small enough compared to the diffusion length and the cooling length, shocks with Mach numbers of 5 and 10 behave very similarly to their single fluid counterparts and display thermal overstability for appropriate radiative cooling laws. For strong shocks one would hope to be able to tune the ratios of the energy transfer length, diffusion length, and cooling length to obtain structures showing a continuous range of behaviour from steady cosmic-ray dominated flows to overstable flows with small cosmic ray pressure everywhere. Though we know that values of the ratios can be selected to give cosmic-ray dominated flow or flow resembling that in a single-fluid radiative shock, we do not know that a smooth transition from one type of extreme behavior to the other occurs in general when the ratios vary smoothly. Indeed, attempts made by Wagner et al. (2007) to find a combination of parameters leading to a strong shock solution with a moderate postshock ratio of the cosmic ray and thermal pressures were unsuccessful. Becker & Kazanas (2001) have performed a thorough analysis of the very closely related bifurcation of solution space for adiabatic cosmic-ray modified shocks.

7. Conclusions

Theoretical studies are interesting in themselves, but ultimately one aims to use models to understand observations. So far, the Wagner et al. (2007) models of cosmic-ray moderated radiative shocks have not been used to interpret data. However, Boulares & Cox (1988) attempted to use similar models of adiabatic cosmic-ray modified shocks to interpret optical data for the Cygnus Loop. They did not include energy transfer from the cosmic rays to the thermal fluid due to the Drury & Falle (1986) acoustic instability, and optical data have improved sufficiently that more reliable inferences are now possible.

Wagner et al. (2009) used time-dependent adiabatic shock models, incorporating energy transfer from the cosmic rays to the thermal fluid in the manner described above, to interpret optical emission data for knot g in the Tycho supernova remnant. They inferred values for the diffusion coefficient, the injection parameter, and the energy transfer timescale of 2×10^{24} cm^2 s^{-1}, 4.2×10^{-3}, and 426 yr, respectively.

The injection parameter is defined in Eq. (9) of the paper by Wagner et al. (2009). It is the fraction of thermal particles, passing through a sub-shock in the thermal fluid, that are injected at the sub-shock into the cosmic ray fluid with an energy per particle exeeding the mean thermal energy by a factor of a few. The value inferred by Wagner et al. (2009) is consistent with the results obtained from hybrid simulations (Bennett & Ellison 1995), measurements near the Earth's bow shock (Trattner & Scholer 1994), and other analytic and numerical work conducted by Malkov & Völk (1995), Malkov (1998), and Gieseler et al. (2000).

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