HEATING BY ACOUSTIC WAVES OF MULTIPHASE MEDIA

Doron Chelouche\textsuperscript{1}

School of Natural Sciences, Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA; doron@ias.edu

and

Canadian Institute for Theoretical Astrophysics, 60 St. George Street, Toronto, ON M5S 3H8, Canada

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ABSTRACT

We study the emission and dissipation of acoustic waves from cool dense clouds in pressure equilibrium with a hot, volume-filling dilute gas component. In our model, the clouds are exposed to a source of ionizing radiation whose flux level varies with time, forcing the clouds to pulsate. We estimate the rate at which acoustic energy is radiated away by an ensemble of clouds and the rate at which it is absorbed by, and dissipated in, the hot dilute phase. We show that acoustic energy can be a substantial heating source of the hot gas phase when the mass in the cool component is a substantial fraction of the total gas mass. We investigate the applicability of our results to the multiphase media of several astrophysical systems, including quasar outflows and cooling flows. We find that acoustic heating could have a substantial effect on the thermal properties of the hot phase in those systems.

Key words: cooling flows – galaxies: Seyfert – ISM: clouds – ISM: jets and outflows – quasars: general – waves

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1. INTRODUCTION

Multi-thermal-phase gas configurations are often encountered in astrophysics. For example, interstellar gas is known to consist of several thermally distinct components whose temperatures are in the range 10^{2}–10^{6} K (e.g., McKee & Ostriker 1977). Gaseous halos of L\textsuperscript{*} galaxies constitute cool (10^{4} K) gas condensations embedded in a hot (10^{6} K) volume-filling virialized gas (e.g., Mo & Miralda-Escude 1996; Chelouche et al. 2007 and references therein). The intracluster medium (ICM) of nearby clusters shows rich structure of cool ionized filaments embedded in a hot X-ray emitting material and extending to large scales (e.g., Conselice et al. 2001; Fabian et al. 2003). A similar structure is also observed around radio-loud quasars (RLQs) where a considerable fraction of the mass of the gaseous nebulae lies in cool clumps of gas (e.g., Crawford & Fabian 1992; Fu & Stockton 2006). More recently, it has been realized that many astrophysical outflows are also multiphase with cool condensed material embedded in a hotter and more dilute ambient medium. These systems include: planetary nebulae (e.g., Meaburn et al. 1992), stellar winds (e.g., Bouret et al. 2005), and quasar flows (e.g., Das et al. 2005).

The physical mechanisms responsible for multiphase gas configurations in different systems are quite diverse. A partial list includes thermal instability and compression by radiative shocks in hot material, and evaporation and gravitational binding of cool material. While our understanding of the complex physics leading to multiphase structures is incomplete, it is well established that such systems are a widespread phenomenon.

Recent studies suggest that some multiphase systems seem to suffer from a heat “deficit.” One example is that of highly ionized X-ray outflows from the central regions of Seyfert galaxies that are believed to be thermally driven and are seen to reach high velocities despite the effect of adiabatic cooling (e.g., Chelouche & Netzer 2005). An analogous case to that are the large-scale narrow line region (NLR) outflows in active galactic nuclei (AGNs) where the effect of adiabatic cooling is even more pronounced (e.g., Everett & Murray 2007). These discrepancies may be alleviated if a yet unidentified heating source is lurking in those systems which would balance adiabatic losses. Another example is that of cooling flows in which the time for radiative cooling of the hot component appears to be short compared to the Hubble time, yet the gas does not cool significantly. Various explanations have been put forward to explain the cooling flow problem including thermal conduction (e.g., Fabian et al. 2002; Zakamska & Narayan 2003), \textit{PdV} work done by expanding radio bubbles that are inflated by (recently activated) AGNs (e.g., Fabian et al. 2003 and references therein; see also Mathews et al. 2006), and the dissipation of gravitational energy via cool condensations falling through the hot gas (Murray & Lin 2004; see also Dekel & Birnboim 2007).

In this paper, we wish to address the general problem of the heating/cooling balance in multiphase media around sources with time-varying ionizing fluxes. Flux variability is a characteristic of many astronomical objects and of active (accreting) systems in particular (see, e.g., Geha et al. 2003 for the case of quasars; Zezas et al. 2007 for a study of X-ray binaries). While the examples given in this paper focus on quasar-related phenomena, we emphasize that the general processes outlined here may apply to other systems such as X-ray binaries and variable stars.

This paper is organized as follows. In Section 2 we present a general analytic formalism that describes the radiative forcing of clouds which causes them to pulsate and emit acoustic waves into their surrounding medium. Absorption of acoustic radiation and several heat transport mechanisms are also discussed. We address a few specific systems to which this physical mechanism may apply in Section 3. Numerical calculations confirming some aspects of our analytic approximations are also presented. Our conclusions follow in Section 4.

2. THE EMISSION AND DISSIPATION OF ACOUSTIC WAVES

2.1. General Setup

Here we consider a generic configuration of a multiphase medium by assuming dense and cool gas condensations (clouds)
with time-averaged temperature $T_c$ embedded in a hot, dilute, volume-filling medium at temperature $T_h$ (see Figure 1). We assume that the two phases are, in a time-average sense, in pressure equilibrium such that

$$\rho_h = \rho_c \frac{T_c}{T_h}, \quad (1)$$

where $\rho_c$ and $\rho_h$ are the densities of the cool and hot components. Characterizing such an equilibrium requires knowledge of the relevant heating and cooling mechanisms in each phase. These processes are complicated, but we note that, generally, cooling is $\propto \rho^2$; hence the cooling time would be shorter for the dense and cool phase compared to the dilute and hot one. In a steady-state thermal balance, this is also true for the heating rates.

Below we show that a fraction of the photon energy which is absorbed by the cool gas can be redirected to heat the hot ambient medium by means of acoustic waves. Such a process naturally occurs when the cool phase is photo-heated by a time-varying radiation field (e.g., that of a quasar). Clouds distributed throughout the volume of the system would change their pressure due to the varying radiative heating and would therefore pulsate. As such, they would act as bells (or monopole loudspeakers) emitting acoustic radiation into their environment. Unlike Murray & Lin (2004), our model for the heating of the volume-filling hot medium does not require differential velocities between the phases to operate, and does not necessarily lead to the grinding of the cool phase.

2.2. Emission

Consider an isolated spherical cloud which is exposed to a source of ionizing flux that varies with time $t$ (Figure 1). Consider also a specific mode of oscillation such that the flux

$$F(t) = F_0 + \delta F \cos \omega t, \quad (2)$$

where $t_0 = 2\pi \omega^{-1}$ and $\delta F$ is the amplitude of variation. We further assume that

$$\max(t_{\text{cool}}^c, t_{\text{heat}}^c) < t_0 \ll \max(t_{\text{cool}}^h, t_{\text{heat}}^h), \quad (3)$$

with $t_{\text{cool}}^c$ and $t_{\text{cool}}^h$ ($t_{\text{heat}}^c$ and $t_{\text{heat}}^h$) being the cooling time and heating time of the cool (hot) phase, respectively (see Section 3 for the discussion of specific systems). In this regime, the cloud reacts instantaneously to the varying flux by changing its temperature, and hence its pressure (we check the validity of this condition for specific systems in Section 3). So, for example, as the level of ionizing flux rises, more energetic electrons are injected into the gas thereby increasing its temperature. The cloud, being over-pressured compared to its environment, would expand into the ambient medium. For large enough flux variations ($\delta F / F \sim 1$), the cloud’s temperature and pressure ($P$) variations satisfy $\Delta T_c / T_c \sim \Delta P / P \sim 1$ (see Section 3 for detailed photoionization calculations). In this case, the cloud will expand at roughly its sound speed, $c_s$. We neglect any time dependence of $c_s$ in the present analysis as this is proportional to $\sqrt{\Delta P / P}$ which is of order unity. We note that since $t_0 \ll t_{\text{cool}}^h$ the hot phase will not react to flux variations of this duration and its properties may be considered constant over $t_0$. The last condition may be relaxed if the hot component is in a range of parameter space where $\partial \ln(T)/\partial \ln(F) = 0$, as would be the case for gas at the Compton temperature.

In what follows, we shall work in the long-wavelength regime, namely, $t_0 \gg R_c / c_h$, where $R_c$ is the cloud radius (see below for a more general definition of $t_0$, which takes into account the finite cooling time of the cloud). At much higher frequencies a phase develops between the gas pressure and velocity (as they become orthogonal on small scales) so that the cycle-averaged radiation is small.

Acoustic flux is often over-estimated in the literature. When a cloud, or a piston, expands subsonically (indeed $c_s \ll c_h$ by construction in our case), the ambient medium in its immediate environment would be effectively incompressible and would pulsate with the cloud not producing sound (i.e., compression) waves. Sound waves are produced once the surrounding medium has not had time to respond to the changing volume of the region interior to it which occurs at a distance $\sim c_h t_0$ from the cloud. This distance marks the transition to the radiative zone (see the Appendix). From the continuity condition, the velocity at that location

$$\dot{\xi} = c_s \left(1 + \frac{c_h t_0}{R_c}\right)^{-2}. \quad (4)$$

Hence, for large enough $t_0$, $\dot{\xi} \ll c_s$. The acoustic luminosity radiated away by a single pulsating cloud would therefore be

$$L_{\text{acoustic}} = 2\pi R_c^2 \rho_h c_s^2 c_h^2 \left(1 + \frac{c_h t_0}{R_c}\right)^{-2}. \quad (5)$$

Clearly, for large enough $t_0$, $L_{\text{acoustic}}$ becomes very small.

It is interesting to compare the total energy emitted over one cycle to the energy stored in the hot gas within a shell defined by the surface of the cloud at a distance $r = R_c$ and $r = R_c + c_h t_0$. As $\dot{\xi}$ declines rapidly with $r$, we can write

$$L_{\text{acoustic}} \frac{t_0}{4/3\pi R_c^4 \rho_h c_s^2} \propto \frac{R_c}{c_h t_0}. \quad (6)$$

Hence, for long enough wavelengths, this ratio is $\ll 1$ and most of the $PdV$ work done by the cloud by expanding into the ambient medium is returned to it during the compression phase (e.g., Leighton 1997, p 129; the Appendix). This is also why typical loudspeakers are rather inefficient in producing sound converting, on average, only $\sim 1\%$ of the electric power to audible acoustic power.
The ratio of acoustic energy emitted by all the clouds over the cooling timescale of the hot phase (from adiabatic or radiative losses) and the thermal energy stored in the hot phase, $E_h$, is

$$\frac{E_{\text{acoustic}}}{E_h} = \frac{3}{2} \frac{\epsilon_V}{1 - \epsilon_V} \left( \frac{c_c}{c_h} \right)^2 \frac{c_h \rho_c}{R_c} \left( 1 + \frac{c_h t_{wo}}{R_c} \right)^{-2}$$

$$\sim \epsilon_V \left( \frac{c_c}{c_h} \right)^2 \frac{R_c}{c_h t_{wo} t_0},$$

(7)

with $\epsilon_V$ being the volume-filling factor of the cool phase. The last expression is valid in the limit $c_h t_{wo}/R_c \gg 1$ and $\epsilon_V \ll 1$. Clearly, a prerequisite for effective acoustic heating is that $E_{\text{acoustic}} \gg E_h$. This is achieved for short $t_{wo}$. Nevertheless, $t_{wo}$ cannot be arbitrarily short since it must satisfy

$$t_{wo} \geq t_0 = \max \left( \frac{R_c}{c_h}, \frac{\rho_c c_c^2}{\Lambda(T, \rho_c, F)} \right),$$

(8)

where $\Lambda$ is the net cooling/heating rate per unit volume averaged over half a cycle. If the converse is true then the clouds’ thermal state would change little with time and radiative forcing would be less efficient (this is shown to be the case in Section 3). For $t_{wo} > t_0$, $E_{\text{acoustic}}/E_h \propto t_0^{-2}$, hence $t_0$ is the mode which is most efficient in converting photon flux to acoustic flux.

It is interesting to compare the acoustic luminosity emitted by the cloud to its photo-heating rate

$$L_{\text{acoustic}} \approx \frac{R_c}{c_h t_{wo}} \left( \frac{c_c}{c_h} \right)^2 \frac{\rho_c c_c^2}{\Lambda(t_{wo})} \leq \left( \frac{c_c}{c_h} \right)^2.$$

(9)

Clearly, only a small fraction of the photon-heating luminosity is transformed to acoustic luminosity (e.g., at most $\sim 1\%$ will be converted to acoustic luminosity for $T_c = 10^8$ K and $T_h = 10^6$ K). For the case in which the emitted acoustic radiation is fully absorbed in the system then acoustic heating would overcome the cooling of the hot phase once

$$\epsilon_V \frac{\Lambda(\rho_c)}{\Lambda(\rho_h)} \left( \frac{c_c}{c_h} \right)^2 \sim 1,$$

(10)

where we have used Equation (9) and our assumption of pressure equilibrium. If the ratio of the cooling rates for the hot and cold phases is $\sim (\rho_h/\rho_c)^2$ (as would be the case if, for example, the thermal properties of the hot phase are determined primarily by photo-heating; see Section 3) then we require that the mass fraction of the cool component, $\epsilon_M$, satisfies

$$\epsilon_M \sim \frac{\rho_c}{\rho_h} \epsilon_V \sim 1.$$  

(11)

This brings us to an important conclusion: the mass of the cool phase should be comparable to that of the hot phase for acoustic heating to be effective. We discuss this result more quantitatively in Sections 3.1–3.3.

It is possible to analytically estimate the typical size of clouds that can give rise to significant acoustic heating. A natural scale comes from the requirement for a minimal $t_0$ which occurs for $R_c/c_h = \rho_c c_c^2/\Lambda$ (see Equation (8) and the numerical results of Section 3). This gives the following order-of-magnitude estimate:

$$R_c \sim \frac{t_{cool}}{c_h},$$

(12)

i.e., $R_c/l$ is on the order of the ratio of the cooling time of the cool phase to the sound-crossing timescale of the hot phase. A specific case worth mentioning is that of adiabatically cooling/heating, thermally-driven systems (such as X-ray and NLR quasar outflows). Here, the thermal state of the hot medium satisfies

$$P \sim \frac{\Lambda}{c_h}.$$

(13)

That is, the time it takes for the entire volume to heat (or cool) is on the order of the dynamical time. Using this property of such systems, we can readily estimate $R_c$ to be

$$R_c \sim \left( \frac{c_c}{c_h} \right)^{4} l \left( \frac{\rho_h}{\rho_c} \right)^{2} l$$

(14)

(in this case, the required number of clouds in the system is roughly $(\rho_c/\rho_h)^2$). We emphasize, however, that this provides only a rough estimate for $R_c$ and that, in fact, there is a range of cloud sizes which can induce significant acoustic heating, as we demonstrate for a few specific systems in Section 3.

2.3. Absorption

The emission of acoustic energy by a cool cloud does not guarantee that the energy will dissipate over the relevant spatial scales required to effectively heat up the volume. Dissipation of acoustic energy in the hot medium occurs via absorption (and conductance) as well as by steepening of acoustic waves into weak shocks. The latter process is negligible in our case since the clouds pulsate subsonically and the wave amplitude is quickly diminished in the spherical case (see Stein & Schwartz 1972).

The relevant dissipation length scale due to absorption of radiation is (e.g., Mathews et al. 2006)

$$l_d \sim \frac{1}{\mu} \left( \frac{\rho_h}{\rho_c} \right)^{1/2} l_{\text{co}} \left( \frac{t_{wo}}{2\pi} \right)^{2},$$

(15)

where $\mu$ is the effective viscosity (including both the effects of viscosity and conduction; e.g., Fabian et al. 2005). Here we take the usual Braginskii-Spitzer (e.g., Spitzer 1962) value for high-temperature solar composition gas $\sim 10^{-10} \eta P_h^{5/2}$ cm$^{-1}$ s$^{-1}$ (e.g., Lang 1999, p 208) which is applicable to, e.g., the ICM for $\eta = 10^{-2}$ to 1 (Narayan & Medvedev 2001; Fabian et al. 2005; but see Ettori & Fabian 2000 for possibly much lower values). Due to the lack of observational constraints on the conductivity of other systems (e.g., quasar outflows), we shall assume values similar to those of the ICM.

Rewriting Equation (7) with dissipation included, we obtain a generalized condition for the importance of acoustic heating,

$$\frac{E_{\text{acoustic, dissipated}}}{E_h} = \frac{E_{\text{acoustic}}}{E_h} \left( 1 - e^{-l/l_d} \right) \gtrsim 1.$$  

(16)

For $l_d \gg l$, absorption is inefficient and most of the acoustic energy (a fraction $\sim 1 - l/l_d$ of it) will escape the system. Absorption is efficient over the entire volume for $l_d \sim l$. For $l_d \ll l$, absorption is very efficient yet is localized to the environment of the clouds. In this case several additional conditions are required to effectively heat up the entire volume. These are discussed below.
2.3.1. The Case of \( l_d \ll 1 \)

For volumetric heating to be important, we require many clouds which are homogeneously distributed throughout the volume of the system and/or the presence of some heat transport mechanism. For clouds distributed randomly in space (as indeed seems to be observationally supported; see Section 1), the characteristic distance between clouds is \( \approx \epsilon_v^{1/3} R_c \). If no heat transport mechanism is operating then we require

\[
\epsilon_v^{1/3} \frac{l_d}{R_c} \geq 1
\]

so that the dissipation of acoustic waves due to all clouds occurs throughout the volume. A much less restrictive case is that in which heat conduction and/or advection are present. In this case, even if the above condition is not satisfied, heat could still be distributed over the entire volume.

Heat conduction is due to free electrons whose velocity is, \( v_e \approx \sqrt{3k_B T_e/m_e} \approx 6 \times 10^5 \sqrt{T_e/10^6 \text{ K}} \) km s\(^{-1}\). The propagation of electrons through a plasma takes the form of a random walk with some mean free path, \( \lambda_e \). The largest uncertainty arises in estimating \( \lambda_e \), which depends on the strength and configuration of the magnetic field, \( B \), as well as on the pressure and density of the (hot) medium. If \( B = 0 \) then \( \lambda_e = \lambda_e^{B=0} \approx 10^3 T_e^{3/2}/(\rho_b/m_H) \) cm (where \( m_H \) is the mass of a hydrogen atom; see Cowie & McKee 1977). When \( B > 0 \) the medium becomes anisotropic with \( \lambda_e \) being on the order of the Larmor radius across magnetic field lines. For a detailed discussion of these issues, see Lazarian (2006, and references therein). Here we assume that \( 10^{-2} < \lambda_e/\lambda_e^{B=0} < 1 \) (Narayan & Medvedev 2001). Hot electrons must traverse a distance on the order of a random walk with some mean free path,

\[
\Delta \sim \lambda_e
\]

In addition to conductance, heat may be advected by, e.g., turbulent motion in the gas (we do not consider here the additional heating by the dissipation of turbulent energy; e.g., Chelouche & Netzer 2005). For a Kolmogorov-type transsonic turbulence, the velocity of eddies of size \( l_e \) is \( v_e = c_{th}(l_e/l)^{1/3} \) and for efficient advection we therefore require

\[
\epsilon_v^{-2/3} \frac{R_c^2}{v_e l_c} \lesssim 1.
\]

In cases where the medium is not in thermal equilibrium (i.e., \( T_d \neq T_c \)) we use \( T_c \) for the temperature of the medium. If the system is in thermal equilibrium, \( T_d = T_c \).

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A further caveat concerns the role of magnetic fields in determining the propagation of sound waves in the medium. Better estimates for the magnitude of (magneto-)acoustic heating will require not only detailed numerical simulations but also a better understanding of the individual systems to which this process may apply.

3. APPLICATIONS TO ASTROPHYSICAL SYSTEMS

In this section we examine how acoustic heating can be important in astrophysical environments. It is not the purpose of this paper to cover all possible cases but rather to study the applicability of the process to a few specific systems. In all cases considered below there is either an active ionizing source with a varying flux or one has recently been active. Here we consider examples pertaining to quasar outflows and to cooling flows. To this end, we have taken fiducial parameter values from the literature concerning the physical properties of the cool and hot phase but note the appreciable uncertainties associated with them. These parameter values include rough estimates for \( T_c, T_h, \) and \( \rho_c \). Estimates for the total size of the system, \( l \), and its cooling time, \( t_c^{cool} \), are also taken from the literature. The characteristic values of \( \epsilon_v \) and \( R_c \) are very poorly constrained in those systems and are therefore treated as free parameters.

A major difficulty when estimating the response of the cloud to radiative forcing is to properly assess the net heating/cooling function \( \Lambda \) (Equation (8)) which depends on whether the gas is in photoionization and thermal equilibrium at all times (as would be the case if the heating and cooling timescales are the shortest in the problem) or whether its thermal state depends on its history in some intricate way. To keep the problem tractable, we estimate the net heating/cooling function by the value of the cooling function under steady-state conditions (in which case its values match those of the heating function). For solar metallicity, optically-thin gas exposed to a type-I quasar continuum (Sazonov et al. 2005), the heating rate does not have a strong dependence on the temperature, varying by a factor of order unity in the range \( 10^4 < T_c < 10^8 \) K, so that an adequate approximation for our purpose is

\[
\Lambda(T, \rho) \simeq 10^{-23}(\rho_c/m_H)^2 \text{ erg s}^{-1} \text{ cm}^{-3}.
\]

This value shall be used to obtain an order-of-magnitude estimate for the heating/cooling timescale of the cloud (Equation (8)).

To check the validity of the above approximation for \( \Lambda \) in cases where strict thermal equilibrium is not justified, we have calculated several time-dependent photoionization models using CLOUDY c07.02 (Ferland et al. 1998) and assuming a light curve, of a fixed amplitude, varying the mode frequency, i.e., \( t_{\omega} \). Isochoric conditions are assumed for the calculations since \( c_{ei}/c_{th} \ll 1 \) and we focus on the threshold of the long-wavelength regime (see below). Calculations were carried out for the case of \( \rho_c/m_H = 10^5 \) cm\(^{-3}\) and placing the cloud at 1 pc from the quasar so that its steady-state temperature—if it were exposed to a constant flux \( F \) of \( \sim 8 \times 10^4 \) K (corresponding roughly to X-ray outflow temperatures; see Section 3.1). The results, shown in Figure 2, indicate that our estimate for the net cooling function (i.e., \( t_c^{cool} \)) using steady-state values is indeed reasonable. In particular, the cloud does not react to the varying flux level of the source for \( t_{\omega} \ll t_c^{cool} \) and radiative forcing would be inefficient. The cloud temperature does follow the light curve for \( t_{\omega} \sim t_c^{cool} \), albeit with a phase, and its temperature fluctuations, \( \Delta T_c \), are almost as large as those obtained for \( t_{\omega} \gg t_c^{cool} \) (where
little or no phase is present since the cloud reacts instantly to the source’s flux level. We note here that almost all phase is absent since the cloud reacts instantly to a time-varying flux of a sinusoidal form (denoted by a dotted line; see legend). All quantities are shown relative to their mean values. A phase develops and the temperature variation amplitude is somewhat lower in the range $(0.1–100) \times t_\omega$. The cloud’s temperature variation is quenched for $t_\omega \ll t_\text{cool}$. These calculations justify our approximation of the heating/cooling rates by their steady-state values (see Section 3).

3.1. X-ray Outflows in Seyfert 1 Galaxies

The parameters for X-ray gaseous outflows from Seyfert 1 galaxies which we adopt here are: $T_e = 8 \times 10^4$ K, $T_h = 10^8$ K, $\rho_c/m_H = 3 \times 10^3$ cm$^{-3}$, $l = 3$ pc, and $t_{cool} = 10^4$ years (Chelouche & Netzer 2005). Considering Equation (16), there is a large range of the parameter space in which acoustic heating is considerable and can balance adiabatic cooling (see Figure 3). In particular, such heating would be effective—that is, comparable to radiative heating—for $\epsilon_V \gtrsim 10^{-2}$, i.e., once the mass in the cool phase is comparable or larger than that of the hot phase (see Equation (11)). Cloud sizes should be in the range $10^{14}-10^{15}$ cm ($R_c/l \sim 10^{-4}$; see Equation (14)) for acoustic heating to be effective. Such values are consistent with full occultation of the X-ray source in Seyfert 1 galaxies (e.g., Chelouche & Netzer 2005). We note that if $\epsilon_M \gtrsim 10$ then acoustic heating may even dominate over photo-heating resulting in a hot-phase temperature that would exceed the Compton temperature.

3.2. Extended NLR Outflows in Seyfert Galaxies

Little is known about the physical properties of NLR flows, and the existence of a hot medium is mainly inferred from the dynamics of the low temperature, optically-detected gas. We take fiducial values of $T_e = 10^4$ K, $T_h = 10^8$ K and consider multiphase gas on $\sim 30$ pc scales (e.g., Das et al. 2005; Everett & Murray 2007). For luminosities typical of type-I Seyfert galaxies, the implied density of the hot phase on such scales is of order $10^3$ cm$^{-3}$ (Everett & Murray 2007; see also Chelouche & Netzer 2005) hence $\rho_c/m_H = 10^3$ cm$^{-3}$. Here, the dynamical time is on the order of the adiabatic-cooling time which is of order $10^7$ years (Everett & Murray 2007). In this case we find a wide range in parameter space where acoustic heating can be important. Everett & Murray (2007) quote values for the filling factor of the cool phase as high as $10^{-2}$. Figure 3 shows that, in this case, the emission of acoustic energy by clouds with $R_c \sim 10^{16}$ cm could contribute significantly to the heating–cooling balance of the hot phase. Cloud sizes of this size cannot be individually resolved by current observations yet similar cloud sizes have been inferred from density and column density measurements of UV absorber properties on similar scales (e.g., Kraemer et al. 2001 and references therein). Arguments applying to X-ray outflows (Equations (18) and (19)) apply here too.

3.3. Cooling Flows in Galaxy Clusters

Observations of RLQs show the presence of intrinsically bright O ii and O iii emission line regions with apparent sizes of a few $\times 10$ kpc that consist of numerous unresolved cool clouds (e.g., Fu & Stockton 2006 and references therein). It is thought that at least some RLQs and radio galaxies inhabit the cores of galaxy clusters that possess massive cooling flows toward their centers (e.g., Crawford & Fabian 1992). In this case, the optical emission is thought to originate from cool clouds embedded within the hot medium (Crawford & Fabian 1992). It is not known whether such multiphase gas configurations are
a property of all cooling flows in galaxy clusters; nor is it clear if all cooling flow clusters which do not cool effectively contain active or recently active nuclei (though they do seem to have a > 50% duty cycle for jet activity; Fabian & Sanders 2007). Nevertheless, we can use typical cloud parameters inferred from optical observations and ambient medium parameters deduced from X-ray studies: \( T_c = 2 \times 10^4 \text{ K} \), \( T_h = 10^7 \text{ K} \), \( \rho_c/m_H = 10 \text{ cm}^{-3} \), \( l = 5 \times 10^5 \text{ pc} \), and \( t_{\text{cool}} = 7 \times 10^9 \text{ years} \) (see, e.g., Dunn & Fabian 2006; Fu & Stockton 2006). Figure 3 shows that, for \( \epsilon_{\text{V}} \gtrsim 10^{-4} \) (indicating that the mass of the cool component is \( \gtrsim 10\% \) that of the hot phase; see Fu & Stockton 2006), clouds of size \( \sim 0.1 \text{ pc} \) could efficiently balance radiative cooling in those systems. Interestingly, similar cloud sizes have been deduced by Hamann et al. (2001) for the clouds seen in absorption toward quasars.

It should be noted that the mass of the cool gas at the centers of currently inactive cooling flow clusters (i.e., those which do not show optical quasar activity) is rather uncertain. While the inferred mass of the CO emitting (50 K) gas is of order 10% of the hot X-ray gas mass (Salomé et al. 2006; Fabian et al. 2006), the mass of the H\( \alpha \) emitting gas at \( \sim 10^4 \text{ K} \) could be \( \sim 100 \) times lower (Fabian et al. 2008). However, these mass estimates depend on the gas composition as well on the line excitation mechanism; the latter is largely unknown (e.g., Sabra et al. 2000; Hatch et al. 2006). Also, it is not clear how good a proxy \( \text{H}\alpha \) emission is for the total mass of cool gas in those regions and how the properties of the cool phase depend on the presence of an active nearby quasar. For example, the much larger fraction of cool, \( 10^4 \text{ K} \), gas around active quasars (Fu & Stockton 2006) could originate from the CO emitting cold phase seen around nonactive objects which quickly reacts to changes in the ionizing flux level. We also note that larger values of \( \epsilon_{\text{V}} \) (hence \( \epsilon_{\text{M}} \)) would be required for efficient acoustic heating if the combined duty cycle of intracluster active sources is much smaller than unity (Shen et al. 2007). Given the uncertainties associated with the duty cycle of quasars in cooling flow environments and the properties of the cooling flow itself, it is difficult to assess just how important acoustic heating is, in the form considered here.

### 4. Conclusions

In this paper we have presented a simple model for estimating the effect of acoustic heating by radiatively forced pulsating clouds on the thermal state of a hot ambient medium. We find that smaller clouds are more efficient acoustic emitters as long as their cooling time is longer than the oscillation period. Acoustic heating is significant when the mass of cool clouds is a non-negligible fraction of the total gas mass. In particular, for large enough mass in cool gas, acoustic heating may even dominate over photo-heating. This implies the possible existence of higher temperature gas around sources with variable flux compared to nonvariable objects with similar characteristics. This work demonstrates that heating of multiphase photoionized gas may depend not only on the mean flux of the source but also on deviations from it, as well as on the structure of the medium itself. We show that there exists a range of clouds sizes which is most efficient in emitting acoustic energy. Applying this model to quasar outflows and cooling flows, we find that acoustic heating could be important in those systems if the typical size of cool clouds is of order \( 10^{-4} \) the size of the system. Better understanding of the multiphase nature of photoionized environments in terms of the relevant densities, cloud sizes, and cooling rates, as well as the properties of the ionizing source (i.e., its power spectrum of variations) are required to properly assess the importance of this effect in the broader astrophysical context.

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Figure 4. “Luminosity,” shown here as the amplitude squared \( \times \text{area at some instance} \), of an outgoing wave driven on the left side with a finite amplitude (a dissipationless wave equation is assumed). Clearly, the amplitude diminishes rapidly toward the radiative zone and the luminosity carried by an outgoing wave is considerably smaller than that which would be naively calculated at the source of motion (see Section 2.2). Note the logarithmic scales in both axes.

APPENDIX

Lagrangian perturbations for the equation of motion of the hot component in spherical coordinates gives

\[
\ddot{r} \xi + c_h^2 \nabla \cdot (\xi) = c_h^2 \frac{\partial}{\partial r} \left( \frac{1}{r^2} \frac{\partial}{\partial r} r^2 \xi \right) \tag{A1}
\]

whose general solution is

\[
\xi = [aj_1(kr) + by_1(kr)]e^{i\omega t}, \tag{A2}
\]

where \( j_1, y_1 \) are the spherical Bessel functions. The boundary conditions for the problem are: (1) a forced oscillator at the wall of the cloud satisfying \( \xi(r = R_c, t) = c_e \exp(i\omega t) \) and (2) a radiatively expanding wave solution at infinity such that \( \xi(r \to \infty) \propto \exp(i\omega t - kr) \). A solution is obtained upon matching the boundary conditions and is shown in Figure 4. Clearly, the flux amplitude drops quickly, and by a large factor, from the surface of the cloud (on the left side) toward the radiative zone. Hence, most of the energy emitted by the pulsating cloud at the start of the cycle is returned to it toward the end so that only a small fraction of the energy is acoustically radiated away. The acoustic flux at large distances from the cloud surface is constant in this example since no dissipative mechanism was included in Equation (A1).