THE EFFECTS OF IRRADIATION ON CLOUD EVOLUTION IN ACTIVE GALACTIC NUCLEI

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Received 2013 September 24; accepted 2013 November 5; published 2013 December 11

ABSTRACT

We report on the first phase of a study of cloud irradiation. We study irradiation by means of numerical, two-dimensional, time-dependent radiation hydrodynamic simulations of a strongly irradiated cloud. We adopt a very simple treatment of the opacity, neglect photoionization and gravity, and focus instead on assessing the role of the type and magnitude of the opacity on the cloud evolution. Our main result is that even relatively dense clouds that are radiatively heated (i.e., with significant absorption opacity) do not move as a whole; instead, they undergo very rapid and major evolution in shape, size, and physical properties. In particular, the cloud and its remnants become optically thin in less than 1 sound-crossing time and before they can travel a significant distance (a few initial-cloud radii). We also find that a cloud can be accelerated as a whole under quite extreme conditions, i.e., the opacity must be dominated by scattering. However, the acceleration due to the radiation force is relatively small, and unless the cloud is optically thin, it quickly undergoes changes in size and shape. We discuss implications for the modeling and interpretation of the broad-line regions of active galactic nuclei.

Key words: hydrodynamics – instabilities – methods: numerical – radiative transfer

Online-only material: color figures

1. INTRODUCTION

There are many situations in astrophysics in which one or a group of objects is exposed to relatively strong radiation produced by a nearby external source. Examples include planets and moons irradiated by their host star, a star irradiated by its companion in a binary system, gas clouds irradiated by a nearby stellar cluster or by an active galactic nucleus (AGN), and the outer part of a flaring accretion disk irradiated by its inner part or by the accretor.

The consequent radiative heating can change the irradiated object in several ways; e.g., it could change its structure, shape, size, and overall appearance. It could also lead to significant mass loss and even acceleration of the cloud away from the source of radiation (by the so-called rocket effect). To some degree, similar changes can be caused by the radiation force (i.e., without radiative heating).

The effects of irradiation are most profound (e.g., cause ablation and destruction) in cases where the radiation energy is relatively high and the mass of the irradiated object is small, so that self-gravity is negligible. Such cases are relevant in a variety of astrophysical environments, e.g., in the interstellar medium (ISM; e.g., Oort & Spitzer 1955; Bertoldi 1989; Bertoldi & McKee 1990; Bally 1995), in planetary nebulae (e.g., Mellema et al. 1998), near the central regions of AGNs (e.g., Mathews 1986 and references therein), and outside AGN host galaxies, in the intergalactic medium (e.g., Donahue & Shull 1987).

The key questions in this context include the following: How does the radiation that is reflected, reprocessed, or transmitted by a cloud compare with the original external radiation? What aspects of and to what degree can the observed structure and kinematics be accounted for by irradiation? What are the dominant processes responsible for dispersing the gas that was initially collected in the cloud? What are the dominant processes responsible for accelerating the cloud? Can a cloud be significantly accelerated before it is dispersed? How do the acceleration and dispersal rates compare with the cloud formation rate?

Answering these questions is hard from both observational and theoretical points of view, because the evolution of real clouds is very complex and too slow to be measured directly by observations. In addition, in only a few cases are clouds spatially well resolved (i.e., those in the nearby ISM; e.g., Bally 1995). Proper modeling of the clouds is further complicated by the fact that many time-dependent and multidimensional processes and effects are involved, e.g., radiative transfer (RT), gas photoionization and heating, and the subsequent development and propagation of ionization and thermal fronts (IF and TF, respectively) and of shocks and discontinuities. Generally, the cloud irradiation problem requires the simultaneous solving of radiation hydrodynamic (R-HD) equations (examples of such studies include Lefloch & Lazareff 1994; Mellema et al. 1998; González et al. 2007; Raga et al. 2007). One important aspect of this problem is that irradiation is anisotropic, and optically thick clouds will cast shadows. Therefore, RT methods for solving the R-HD equations have to treat the shadows accurately (e.g., Davis et al. 2012; Jiang et al. 2012). Effects of magnetic fields and dust increase the level of complexity even more (see, e.g., Krause et al. 2012 and references therein).

1.1. Simple Cases

However, under some special and idealized conditions, the solution to the problem of the evolution of a spherical, cold cloud that is suddenly exposed to external radiation can be quite trivial. For example, in optically thin cases with pure absorption opacity, radiation will propagate very rapidly (faster than sound) throughout a cloud. If the cloud was initially of constant density and in pressure equilibrium with the uniform ambient medium, it will be uniformly heated. Consequently, the cloud will expand without changing its shape and without gaining net momentum (i.e., it will behave like an expanding...
balloon, for weak irradiation, or an exploding sphere, for strong irradiation). We will refer to such cases as "simple example I."

Another class of trivial solutions exists for optically thin clouds with pure scattering opacity. Here again the radiation will propagate throughout the cloud very rapidly, and afterward the cloud will experience a uniform acceleration away from the radiation source. The acceleration will also be constant with time (for small clouds far from the radiation source), and the cloud will gain momentum without changing its size or shape and without mass loss (i.e., in some respects, it will behave like a bullet). We will refer to such cases as "simple example II."

Another simple yet nontrivial example occurs when a cloud is very optically thick because of absorption opacity and is exposed to weak radiation. In this case, the part of the cloud facing the radiation source will be gently heated, and the radiation will penetrate only a thin layer. The IF and TF will move very slowly across the cloud, and there will be no shock. In addition, the cloud will slowly lose mass from its heated part and be in a quasi-steady state. This simple case and the early evolution of other special cases can be and have been studied using analytic methods that make various simplifying assumptions in order to estimate, for example, the mass-loss rate, the final velocity of the neutral cloud, and the shape of the IF (e.g., Oort & Spitzer 1955; Bertoldi 1989).

1.2. Clouds in AGNs

It is challenging to determine what types of clouds are most relevant in a given environment. This is especially true for the so-called broad-line regions (BLRs) in AGNs, because they are spatially unresolved. In most studies that aim at interpreting or modeling the observed line emission and absorption produced in the BLRs, the cloud properties—such as the density, size, and shape—have been assumed (e.g., Mathews 1974, 1982; Blumenthal & Mathews 1975, 1979; Capriotti et al. 1981; Arav & Li 1994; Krolik 1999 references therein).

The presence of broad emission lines (BELs) and broad absorption lines (BALs) in AGN spectra shows that AGN continuum radiation affects the AGN’s immediate environment. BELs are one of the defining spectral features of AGNs. They are observed in optical and ultraviolet spectra and have line wings extending to velocities up to $10^4$ km s$^{-1}$. It is well established that the primary physical mechanism for the production of BELs is photoionization by the compact continuum source of the AGN (e.g., Kwan & Krolik 1981; Ferland & Elitzur 1984; Ferland et al. 1998; Hamann & Ferland 1999; Krolik 1999 references therein). Detailed photoionization calculations presented in these and other studies have yielded relatively tight constraints on some physical conditions of the emitting gas (e.g., the gas temperature $T_g \approx 10^4$ K, the number density $n \approx 10^3$ cm$^{-3}$, the column density $N \geq 10^{22}$ cm$^{-2}$, and the ionizing flux $F_{\text{ion}}$ is so high that the ratio of radiation to gas pressure $\Xi \equiv F_{\text{ion}}/kT \approx 1$). The width of the BELs indicates that the emitting gas is highly supersonic. The shape and position of the BEL profiles have traditionally been explained as being due to lines emitted in a cloudy region without a preferred velocity direction and with a nearly spherical distribution (e.g., Urry & Padovani 1995; Krolik 1999 references therein). We note that another possibility is that the BELs are produced at the base of a wind from an accretion disk (e.g., Murray et al. 1995; Bottorff et al. 1997).

The key issues faced by any cloudy model for the BLRs are stability and confinement of the clouds (for reviews, see Osterbrock & Mathews 1986; Krolik 1999; Krause et al. 2012). In short, the clouds in the BLRs are hydrodynamically unstable and the nature of their confinement is unclear, while the production of new clouds appears to be inefficient and to require rather extreme conditions. In addition, it has been argued that radiation would cause significant shearing and destroy the clouds before they could contribute to the line emission (e.g., Krolik 1988; Mathews & Doane 1990).

As mentioned above, the modeling of irradiated clouds is a very challenging problem. Many previous studies of clouds in AGNs used various simplifying assumptions, and the robustness and applicability of their results remain quite uncertain. Perhaps the most robust result from previous work is that BELs in AGNs are produced by a photoionized and supersonic medium that is optically thick (i.e., $N > 10^{22}$ cm$^{-2}$; e.g., Kwan & Krolik 1981; Ferland & Elitzur 1984; Rees et al. 1989; Snedden & Gaskell 2007). If this medium is indeed made of optically thick clouds, then one must accurately treat RT—in particular, shadows. This requires self-consistently solving time-dependent, multidimensional R-HD equations.

The direction of the flux is not known independently of the energy density. Therefore, methods based on the diffusion approximation cannot represent shadows. This has been demonstrated through the irradiation of very optically thick structures with a beamed radiation field (e.g., Hayes & Norman 2003; González et al. 2007). However, there are other methods, such as the variable Eddington tensor (VET) method, that can capture shadows accurately.

For example, in Davis et al. (2012), algorithms were developed to solve the RT equation using the method of short characteristics to compute the VET. The tests described there show the accuracy of the RT solver for two radiation beams (see Figure 6 of Davis et al. 2012). This solver was implemented in the radiation MHD code Athena (Stone et al. 2008; Jiang et al. 2012). Jiang et al. (2012) presented results from a few test runs of the dynamical evolution of a cloud ablated by an intense radiation field. These tests showed that the HD, as well as MHD, solvers implemented in Athena capture shadows correctly when coupled with the VET method. In particular, by using an input radiation field at two angles, Davis et al. (2012) and Jiang et al. (2012) explored tests in which both umbra and penumbra were formed. This makes the tests more difficult, because ad hoc closures that capture only one direction for the flux will not represent both the umbra and penumbra correctly.

Here, using Athena, we study the time evolution of clouds subjected to a radiation field as strong as those believed to irradiate the gas in AGNs (i.e., radiation pressure comparable to gas pressure). We consider clouds with a range of properties: from optically thin to thick, and with the opacity due to scattering or absorption processes, or both. To explain BELs and BALs, clouds in AGNs must move with high velocities. Therefore, our primary focus is on identifying physical conditions under which a preexisting cloud could be significantly accelerated before it is dispersed.

Athena allows us to explore this wide range of conditions. Nevertheless, our treatment of clouds is quite simplified. For example, our simulations are in two dimensions, and we assume the clouds to be highly ionized. Therefore, we do not follow the development and evolution of the IF. Moreover, we do not include dust grains or magnetic fields. These and other complications could be modeled with the code but are beyond the scope of this preliminary work.

The outline of this paper is as follows. We describe our calculations in Section 2. In Section 3, we present our results.
We summarize our results and discuss them, together with their limitations, in Section 4.

2. METHODS

We solve the R-HD equations in the mixed frame with radiation source terms given by Lowrie et al. (1999). We assume local thermal equilibrium and that the Planck and energy mean absorption opacities are the same. A detailed discussion of the equations we solve can be found in Jiang et al. (2012). The equations are

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \]
\[ \frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{vv} + \mathbf{P}) = -\frac{\partial \mathbf{S}_r}{\partial t}, \]
\[ \frac{\partial E}{\partial t} + \nabla \cdot [(E + P)\mathbf{v}] = -c \frac{\partial \mathbf{S}_r}{\partial t}, \]
\[ \frac{\partial E_r}{\partial t} + \nabla \cdot \mathbf{F}_r = c \mathbf{S}_r, \]
\[ \frac{1}{c^2} \frac{\partial F_r}{\partial t} + \nabla \cdot \mathbf{P} = \mathbf{S}_r. \]  

(1)

where \( \mathbf{P} \equiv \mathbf{P}_i \) with \( \mathbf{I} \) the unit tensor and \( \mathbf{P}_i \) gas pressure, and \( c \) is the speed of light. \( E \) is the total gas energy density,

\[ E = E_g + \frac{1}{2} \rho v^2, \]  

(2)

where \( E_g \) is the internal gas energy density. We adopt an equation of state for an ideal gas with adiabatic index \( \gamma \); thus, \( E_g = P/(\gamma - 1) \) and \( T = P/R_{\text{ideal}} \rho \), where \( R_{\text{ideal}} \) is the ideal gas constant. The radiation pressure \( P_r \) is related to the radiation energy density \( E_r \) by the closure relation

\[ P_r = f E_r, \]

(3)

where \( f \) is the VET. Finally, \( \mathbf{F}_r \) is radiation flux and \( \mathbf{S}_r \) are the radiation momentum and energy source terms, respectively.

Following Jiang et al. (2012), we use a dimensionless set of equations and variables in the remainder of this work. We convert the above set of equations to dimensionless form by choosing fiducial units for temperature, pressure, and velocity as \( T_0, P_0, \) and \( \rho_0 = (\gamma T_0^\gamma / P_0)^{1/(\gamma - 1)} \). Then the units for the radiation energy density \( E_r \) and flux \( F_r \) are \( a_1 T_0^4 \) and \( c a_1 T_0^4 \), respectively. In other words, \( a_1 = 1 \) in our units. The dimensionless speed of light is \( \mathcal{C} = c/a_0 \). The original dimensional equations can then be written in the following dimensionless form:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \]
\[ \frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{vv} + \mathbf{P}) = -\mathbf{S}_r, \]
\[ \frac{\partial E}{\partial t} + \nabla \cdot [(E + P)\mathbf{v}] = -\mathbf{P} \cdot \nabla \mathbf{S}_r, \]
\[ \frac{\partial E_r}{\partial t} + c \nabla \cdot \mathbf{F}_r = \mathbf{S}_r, \]
\[ \frac{\partial F_r}{\partial t} + c \nabla \cdot \mathbf{P} = \mathbf{S}_r. \]

(4)

where the dimensionless source terms are

\[ \mathbf{S}_r(P) = -\sigma_t \left( F_r - \frac{v E_r + v \cdot P_r}{\mathcal{C}} \right) + \sigma_a \frac{v}{\mathcal{C}} \left( T^4 - E_r \right), \]
\[ \mathbf{S}_r(E) = \sigma_a (T^4 - E_r) + (\sigma_a - \sigma_r) \frac{v}{\mathcal{C}} \left( F_r - \frac{v E_r + v \cdot P_r}{\mathcal{C}} \right), \]

(5)

with \( \sigma_a \) and \( \sigma_r \) the absorption and scattering opacities and the total opacity (attenuation coefficient) \( \sigma_t = \sigma_a + \sigma_r \). The dimensionless number \( \mathcal{P} \equiv a_1 T_0^4 / P_0 \) is a measure of the ratio between radiation pressure and gas pressure in the fiducial units. We prefer the dimensionless equations because numbers such as \( \mathcal{C} \) and \( \mathcal{P} \) can quantitatively indicate the importance of the radiation field, as discussed in Jiang et al. (2012).

We solve these equations on a two-dimensional \( x \)-\( y \) plane with the recently developed RT module in Athena (Jiang et al. 2012). The continuity equation, gas momentum equation, and gas energy equation are solved with a modified Godunov method, which couples the stiff radiation source terms to the calculations of the Riemann fluxes. The radiation subsystems for \( E_r \) and \( F_r \) are solved with a first-order implicit backward Euler method. Details of the numerical algorithm and tests of the code are described in Jiang et al. (2012). The VET is computed from angular quadratures of the specific intensity \( I_r \), which is calculated from the time-independent transfer equation

\[ \frac{\partial I_r}{\partial s} = \kappa_r (S - I_r). \]

(6)

Details on how we calculate the VET, including tests, are given in Davis et al. (2012). Most of our simulations are performed using our standard \((x_{\min}, x_{\max}) \times (y_{\min}, y_{\max})\) computational domain, which is \((-0.5, 0.5) \times (-0.5, 0.5)\), and standard resolution, \(512 \times 512\) cells. Initially, the background medium has density \( \rho_0 = 1 \) g cm\(^{-3}\) and temperature \( T_0 = 10^6 \) K. An overdense clump is located in a circular region \( r \equiv x^2/y_0^2 + y^2/y_0^2 \leq 1 \), with \( y_0 = 0.05 \) cm. The density inside this region is \( \rho(x, y) = \rho_0 + (\rho_1 - \rho_0)/[1.0 + \exp(10(r - 1))] \), where \( \rho_1 \) is a free parameter. The clump is in pressure equilibrium with its surroundings, so the interior is colder than the ambient medium. The initial radiation temperature is the same as the gas temperature everywhere. Here we consider opacities due to scattering \([\sigma_s = \sigma_{sa}(\rho/\rho_0)]\), absorption \([\sigma_s = \sigma_{sa}(T/T_0)^{-3.5}(\rho/\rho_0)^2 \text{ cm}^{-1}]\), or both \([\sigma_t = \sigma_s \sigma_a + \sigma_r]\). The radiation flux \( F_r \) is initially zero everywhere. We use reflection boundary conditions on both \( y \)-boundaries and outflow boundary conditions on the right \( x \)-boundary. A constant radiation field with temperature \( T_r = 2T_0 \) is input through the left \( x \)-boundary, where the gas temperature and density are fixed to \( T_0 \) and \( \rho_0 \), respectively. The dimensionless speed of light \( \mathcal{C} = 3.3 \times 10^3 \), and the parameter \( \mathcal{P} = 10^{-3} \).

3. RESULTS

We have performed over 30 different simulations exploring the parameter space and numerical effects. Here we discuss in some detail five simulations that illustrate the evolution of a cloud in significantly different physical regimes: an optically thin and an optically thick cloud with pure scattering opacity (runs S10 and S200, respectively), and mildly optically thick, optically thick, and very optically thick clouds with absorption-dominated opacity (runs A10, A40, and A80, respectively).
Our convention for naming the simulations is as follows: the letter A or S stands for the opacity type, i.e., dominated by absorption or scattering, respectively. The number following the letter corresponds to the initial cloud density, $\rho_1$.

We summarize the properties of the five simulations in Table 1. Columns 2–4 give the input physical parameters, $\sigma_a, 0$, $\sigma_s, 0$, and $\rho_1$, respectively. In Columns 5–9, we list the following initial properties of the cloud: the absorption optical depth $\tau_a = 2 xo \sigma_a$, the scattering optical depth $\tau_s = 2 xo \sigma_s$, the radiation diffusion time across the cloud $t_{\text{diff}} = 4 x^2 \sigma_t / C = \tau_{\text{diff}}$ (where $t_{\text{fs}} = 2 xo / C$ is the free-streaming time), the thermal timescale inside the cloud $t_{\text{th}} = P / (P C \varepsilon \sigma_a)$, and the sound-crossing time $t_{\text{sc}} = 2 xo / c_s$, where $c_s = \sqrt{\gamma P / \rho}$ is the adiabatic sound speed. Finally, Columns 10–12 give the numerical resolution, $n_x \times n_y$, the Courant number, $C_0$, and the time at which we stopped each simulation, $t_f$. For the five runs, we used our standard computational domain.

Figure 1 gives an overview of the cloud evolution in the five runs (columns from left to right correspond to runs S10, S200, A10, A40, and A80). Specifically, the figure shows sequences of density maps overlaid with velocities at five different times (the time increases from top to bottom; the actual time is given at upper left in each panel).

Figure 2 shows several cloud properties as a function of time, illustrating more qualitatively the differences between various runs (the columns’ correspondence to the runs is the same as in Figure 1), as well as the dramatic changes in the clouds with time.

To illustrate how a given cloud would appear to an observer measuring the radiation at the right side of the computational domain, the panels in the top row of Figure 2 present the $x$-component of the normalized radiation field, $F_{1x}$, as a function of the $y$-coordinate. The next row shows $F_{1x}$ at the right boundary, but only at $y = 0$ (i.e., the $(x_{\text{max}}, 0)$ location), and its minimum value along the right boundary (dashed and solid lines, respectively). The fluxes in these panels are normalized so that they are in units of the maximum radiation flux along the right boundary at a given time. The middle panels present the time evolution of the cold gas in the computational domain: the maximum density, total mass, and mass-loss rate (solid, dotted, and dashed lines, respectively). We normalized the maximum density to the initial density of the cloud, $\rho_1$. Our operational definition of “cold” is gas with temperature less than 2 times the initial temperature of the cloud. Therefore, the middle row of panels in Figure 2 can be used to follow the clouds’ heating and subsequent evaporation.

To follow the average cloud motion, the second row from the bottom shows the $x$-position of the center of mass of the cold gas, while the bottom panels show the $x$-component of the...
We start by discussing run S10, which is related to one of the cases mentioned in Section 1.1: simple example II, with scattering opacity only and relatively small optical depth ($\tau_s = 0.2$). The leftmost columns of Figures 1 and 2 show that, as expected, there is no compression (i.e., $\rho_{\text{max}} = 1$), no loss of cold gas, and no shock formation. The cloud is almost uniformly accelerated in the horizontal direction. The implied mass loss of cold gas for $t \geq 27$ is simply the result of the cold cloud’s being advected out of the domain. In addition, the cloud is almost comoving with the ambient medium. We note that the acceleration $a_{\text{rad}}$ due to the radiation force is almost position and time independent in this optically thin case, i.e., $a_{\text{rad}} \approx \frac{2}{10} \times 1.6 \times 10^{-3}$ [one can ignore the velocity-dependent terms in the source term, $S_t(P)$, in the momentum equation, as these are very small, i.e., $v/C \ll 1$]. This acceleration is relatively small. Specifically, the time for an optically thin fluid element to travel a distance equal to the cloud diameter, $t_{\text{dyn}} = \frac{4x_0/a_{\text{rad}}}{V} \approx 11$, is long compared with $t_{\text{sc}} = 0.24$.

Also as expected, the position of the center of mass is a quadratic function of time, and the maximum velocity of the cold gas is very similar to the center-of-mass velocity (see the two lower panels of the left column of Figure 2). The small but nonzero optical depth means that the front side of the cloud experiences a slightly stronger push by radiation than the back side (the acceleration at the back is smaller by a factor of 0.9). Consequently, the cloud is flattened by radiation. This effect is much stronger in run S200, where the cloud is optically thick.

The second column of Figure 1 illustrates how the radiation initially “squeezes” the cloud in run S200: the front is pushed by radiation, while the back side does not move. The radiation pressure acts only from the left side, and the gas pressure inside the cloud is higher than the pressure of the ambient gas. This pressure imbalance leads to lateral expansion that is already noticeable by $t = 12$. The cloud’s evolution is further complicated by the fact that the optical depth decreases (not always monotonically) as a function of $y$ from the cloud center to its edge. For example, as the cloud moves as a whole to the right, it also expands laterally, and its shape starts to resemble a crescent because the more transparent edges are pushed more than the cloud center.

The top panel in the corresponding column of Figure 2 shows clearly that the shadow size increases with time. However, this panel also shows that at later times (i.e., $t \gtrsim 20$) the center is not the most opaque part of the cloud. Instead, the most opaque regions are near the edges where the horns of the crescent bend over toward the center (the second panel from the top shows this too: for $t \gtrsim 20$, the minimum radiation field along the $y$-direction at $x = x_{\text{max}}$ is not at $y = 0$).

Overall, the cloud in run S200 moves more slowly than that in run S10 (compare the second-from-bottom and bottom panels in the corresponding columns in Figure 2). In addition, for run S200, the center-of-mass velocity is lower than the maximum velocity of the cold gas. This difference in the velocities is an
indication of nonuniform cloud evolution. These two examples show that even for a case with pure scattering opacity, the cloud evolution is fast and very different from the movement of a bullet, for which there is no change in shape or size.

The evolution of a cloud with absorption-dominated opacity is even more dynamic and complex, and also faster. We start by discussing run A10, which is related to the other case mentioned in Section 1.1: simple example I, the cloud behaving like a balloon. In this run, \( \tau_s = 2 \times 10^2 \) and \( \tau_{\text{dif}} = 1.2 \times 10^{-3} \), while \( \tau_{\text{fb}} = 2 \times 10^{-6} \). Thus, both \( \tau_{\text{dif}} \) and \( \tau_{\text{fb}} \) are much smaller than \( \tau_{\text{dyn}} \) and the evolution of this absorption-dominated case is much faster than the pure-scattering cases. For example, the middle column of Figure 1 shows that the cloud expands within a time less than 0.2. During its evolution, it does not gain much net momentum and remains almost spherical.

The total mass of the cold gas drops to zero within \( t = 3 \times 10^{-2} \) (see the middle panel in the middle column of Figure 2), which is on the order of \( \tau_{\text{dif}} \). The gas density in the cloud is initially increased by a factor of two, but for \( t > 0.05 \), \( \rho_{\text{max}} \) decreases below 0.01. Note that in this run, the velocity of the center of mass does not correspond to the movement of the whole cloud but rather to the change in location of the boundary between cold and hot (to the rapid propagation of the TF). Hence, the implied center-of-mass velocity can exceed the maximum velocity in these runs. The bottom panel shows that for as long as the cold gas exists, its velocity increases very rapidly with time. After \( \tau_{\text{fb}} \), the only gas left on the grid is the transparent, hot gas moving almost radially away from the center of the grid where the initial cloud was located.

The cloud in run A10 is initially optically thick. However, once the fast TF passes the cloud, the optical depth drops to about 0.6 because of an increase of the temperature alone (i.e., with little change in the cloud density). This quick, isochoric decrease in cloud optical depth is the main reason that the evolution in run A10 resembles the evolution of simple example I, which we referred to as an expanding balloon. Runs with \( \tau_s \) lower than in run A10 show very similar evolution but occurring on a longer timescale. However, runs with higher optical depth show substantial qualitative differences. A good indicator of the expected difference in the evolution is the relation between the diffusion and sound-crossing times.

For run A10, \( \tau_{\text{dif}} < \tau_{\text{sc}} \) and the cloud behaves like a balloon even though it is initially optically thick. However, for run A40, with \( \tau_{\text{dif}} > \tau_{\text{sc}} \) (and \( \tau_{\text{fb}} \) shortened by almost four orders of magnitude), we observe strong evaporation from the irradiated side, the development and propagation of a strong shock inside the cloud, and a few other features unseen in run A10 (compare the third and fourth columns of Figures 1 and 2).

In run A40, the radiation heats the front much faster than it can diffuse across the cloud. Therefore, the cloud loses mass from the left side through a hot outflow. In addition, a very fast and strong shock propagates to the right of the cloud, compressing it and changing its shape. The changes in shape are major: from the initial convex shape, through concave on the front side, to breakup of the cloud into two smaller, elongated clumps.

This cloud’s evolution is far from isochoric. For example, the density on the left side of the cold part of the cloud is increased by a factor of eight (i.e., \( \rho_{\text{max}} = 8 \)) at \( t = 0.9 \). This time corresponds to the maximum compression of the cloud and the smallest shadow (Figures 1 and 2, fourth column). After this, the cloud reexpands and fragments (around \( t = 0.17 \)). Finally, at \( t \approx 0.25 \) even the dense clumps become optically thin as they are heated and dispersed.

As expected, the cloud in run A40 survives much longer than that in run A10. Another consequence of the higher cloud density is that the dense parts of the cloud can travel over a substantial distance before they are heated and dispersed. For example, the second panel from the bottom in the fourth column of Figure 1, for \( t = 0.20 \), shows two dense and optically thick clumps at \( x = 0.18 \)—more than 3 initial-cloud radii from the original location. This movement to the right is caused by the cloud’s hot outflow moving to the left (i.e., the rocket effect).

The push by radiation pressure in this run, as well as in runs A10 and A80, is negligible because \( \tau_{\text{dyn}} \approx 11 \), which is orders of magnitude longer than \( \tau_{\text{fb}} \).

To show the evolution of an even denser cloud, we carried out a simulation for \( \rho_1 = 80 \) (run A80). The rightmost panels of Figures 1 and 2 show the results of this simulation. Overall, the evolution of this denser cloud resembles that of the cloud in run A40. However, there are some quantitative differences. In particular, in run A80 the cloud remains optically thick for about twice as long as in run A40 (compare the second-from-top panels in the fourth and fifth columns of Figure 2). The two clumps that form after the reexpansion phase are denser and more elongated.

The middle through bottom panels in the last column suggest that the cloud disappears at \( t \approx 0.13 \) and reappears around 0.24. However, this is an artifact of our formal definition of the cold phase (gas with temperature less than 2 times the initial temperature of the cloud). The “disappearance” of the cold phase corresponds to the smallest cloud size, with the gas temperature increased as a result of compression rather than radiative heating. However, as the dense cloud later reexpands, the gas temperature drops below our temperature threshold. Later still, the cloud moves to the right, fragments, and continues to be heated by radiation such that at \( t \approx 0.40 \) it is totally dispersed.

4. SUMMARY AND DISCUSSION

We have presented two-dimensional, R-HD calculations of the time-dependent structure of strongly irradiated clouds. Our primary conclusions are the following: (1) Even a relatively dense cloud that is radiatively heated (i.e., with significant absorption opacity) does not move as a whole, instead undergoing very dramatic evolution in its shape, size, and physical properties. In particular, the cloud and its remnants become optically thin within 1 sound-crossing time and before they can travel over a significant distance (a few initial-cloud radii). (2) A cloud can be accelerated as a whole under quite extreme conditions, i.e., the opacity must be dominated by scattering. However, the radiation-force acceleration is relatively small, and unless the cloud is optically thin, it quickly changes size and shape.

Competition among several physical processes determines the cloud evolution. In the cases that we have explored, the most important are the radiation diffusion and heating, the acceleration due to the radiation force, and, finally, propagation of the sound waves and shocks. By comparing the timescales corresponding to each of these processes (see Section 1), one can predict the behavior of a cloud with given initial conditions. For example, as noted in Section 3, for absorption-dominated opacity and \( \tau_{\text{dif}} < \tau_{\text{sc}} \) a cloud will behave like a balloon (simple example I) even if it is initially optically thick. The radiative heating is usually the fastest process. Therefore, simple example II (the bullet-like case) requires very special conditions: scattering-dominated opacity and optical depth much less than unity.
Our goal here was to carry out simulations in a simple and well-controlled way so that we could assess the role of the type and magnitude of the opacity on the cloud evolution. While pursuing this goal, we found that Athena can handle quite a wide range of physical conditions well. Not surprisingly, we also found that the most difficult cases to compute are those with huge density and opacity contrasts, especially when the opacity is dominated by absorption. In these cases, the thermal timescale can be extremely short, so that the energy equation is stiff. To avoid spurious oscillations, we had to increase the numerical resolution and reduce the Courant number (see Columns 10 and 11 in Table 1). For example, in run A80 we reduced $C_0$ to 0.02 from its usual value of 0.8.

In the runs discussed here, we increased the temperature of the incoming radiation by a relatively small factor of two ($T_r = 2T_0$). This corresponds to an increase in the radiation pressure by a factor of 16. Results from our various tests with higher $T_r$ and also higher $p$ confirm the simple expectation that increasing $T_r$ or $p$ results in faster cloud evolution because of increases in the heating rate and cloud acceleration.

As mentioned in Section 1, the BLR clouds are optically thick to absorption and optically thin to scattering. Therefore, the results from runs A40 and A80 are most applicable to the BLRs of AGNs. These results well illustrate the fact that any cloudy model for the BLRs faces the issues of stability and confinement.

These are very serious issues because in our simplified simulations, the cloud velocity was not very different from the ambient velocity. In particular, we did not assume that the cloud is on a Keplerian orbit around the central black hole, as is done in some BLR models (e.g., Pancoast et al. 2011; Krause et al. 2011 references therein). Therefore, here the clouds were not much affected by hydrodynamic instabilities caused by velocity shear. Nevertheless, we found that a cloud cannot be significantly accelerated before it is dispersed (i.e., the rocket effect is not efficient). The main process responsible for the dispersal is radiative heating. One of the implications of these results is that clouds in the BLRs, if they exist, likely take on many different and complex shapes, and this complication should be considered in detailed calculations of cloud line emission.

There are a number of limitations to our results. Probably the most important are that we neglected gas photoionization and assumed frequency-independent (gray) opacities. Additional limitations of our calculations are that they are two-dimensional instead of fully three-dimensional and that we did not include thermal conduction, magnetic fields, or the process or processes responsible for cloud formation. Moreover, in realistic simulations of the BLRs one should also consider computing the evolution of multiple interacting clouds with various properties, not just one cloud as we did here. Our results indicate that such multicloud simulations would be feasible using Athena.

We plan to go beyond some of these limitations in the near future. In particular, we plan to address the issue of cloud formation and subsequent evolution. One possible approach would be to consider the radiative processes and conditions for which the gas is thermally unstable, so that cold condensations can grow on relatively short timescales despite the presence of a strong radiation field (see, e.g., Krolik 1988; Mościbrodzka & Proga 2013 references therein). Such an approach, our intended next step, will involve simulations quite different from those presented here because, among other things, here the gas was thermally stable and not initially in radiative equilibrium.

This work was supported by NASA under Astrophysics Theory Program grants NNX11AI96G and NNX11AF49G. D. P. thanks S. Lepp for discussions and also the Department of Astrophysical Sciences, Princeton University, for its hospitality during his sabbatical when the work presented here was initiated. He also wishes to acknowledge the National Supercomputing Center for Energy and the Environment, for providing computer resources and support. Y.-F. J. was supported by NASA through Einstein Postdoctoral Fellowship grant PF-140109 awarded by the Chandra X-Ray Center, which is operated by the Smithsonian Astrophysical Observatory for NASA under contract NASA-03060.

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