Time-Dependent Photoionization Models

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Abstract

Photoionization modeling codes have been developed over the last three decades, achieving powerful predictions based on a high degree of complexity in terms of the physical processes considered in the simulations. Nevertheless, the temporal dependency of the equations is usually neglected or included through very simplistic approximations. Here we present the first efforts on the development of a self-consistent photoionization model where the energy, ionization balance and radiative transfer equations are considered in their full time-dependent form. With these model we are able to predict the departures from the steady-state of a photoionized gas given the time variability of the radiation source. These results are particularly applicable to active galactic nuclei outflows where the energy source, the optical/UV/X-ray continuum, is highly variable.

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Introduction

Traditionally, plasma photoionization is calculated from the condition of **statistical equilibrium**, which means that the ionization and recombination rates are balanced to each other for the local gas temperature, density, and radiation field. Statistical equilibrium assumes infinitely fast rates and an instantaneous adjustment to the local thermodynamic and radiation state. However, if the local state changes in time and if the timescale to reach ionization equilibrium is longer than the dynamic timescale, then it is necessary to take into account the full temporal dependence of the state equations.

There are many astrophysical systems in which time-dependent photoionization (TDP) modeling is not only applicable, but necessary. Some examples include the **interstellar medium** [1-2], **H ii regions** [3-4], **planetary nebulae** [5-7], **novae** and **supernovae** [8-10, 17], the reionization of the **intergalactic medium** [11-16], ionization of the **solar chromosphere** [18], **Gamma ray burts** [19-20], **accretion discs** [21], **active galactic nuclei** [22-24], and **quasars** [25]. Nevertheless, self-consistent calculations of photoionized media that vary with time are scarce or non existent.

We present preliminary results on the development of a photoionization model where the energy, ionization balance and radiative transfer equations are considered in their full time-dependent form.

Methodology

In order to simplify an otherwise cumbersome problem, we consider a gas 1-dimensional, plane-parallel slab of gas composed entirely of hydrogen. Furthermore, each H atom is view as a simple two-level system, i.e., the ground state and the continuum. Thus, no excited states are included in these simulations. For the calculation of the level populations we include photoionization plus collisional excitation**,** and radiative recombination. Under these assumptions, the **level population equation** is:

$$dn_1/dt = -n_1\gamma - n_1 n_e\beta + n_2 n_e\alpha$$

where $n_{1/2}$ is the population of levels 1/2, n_e is the electron density, γ is the photoionization rate, and β and α are the collisional ionization and radiative recombination coefficients. These last two quantities depend on the temperature of the gas, which is determined by the **energy equation**:

$$dT/dt = 2/(3n_e k)\, dQ/dt = \Gamma - \Lambda$$

where Γ contains the sum of the photoionization and Compton heating, while Λ is the sum of the recombination, Compton and collisional excitation cooling. However, these quantities also depend on the local radiation field, given by the well-known **radiative transfer equation:**

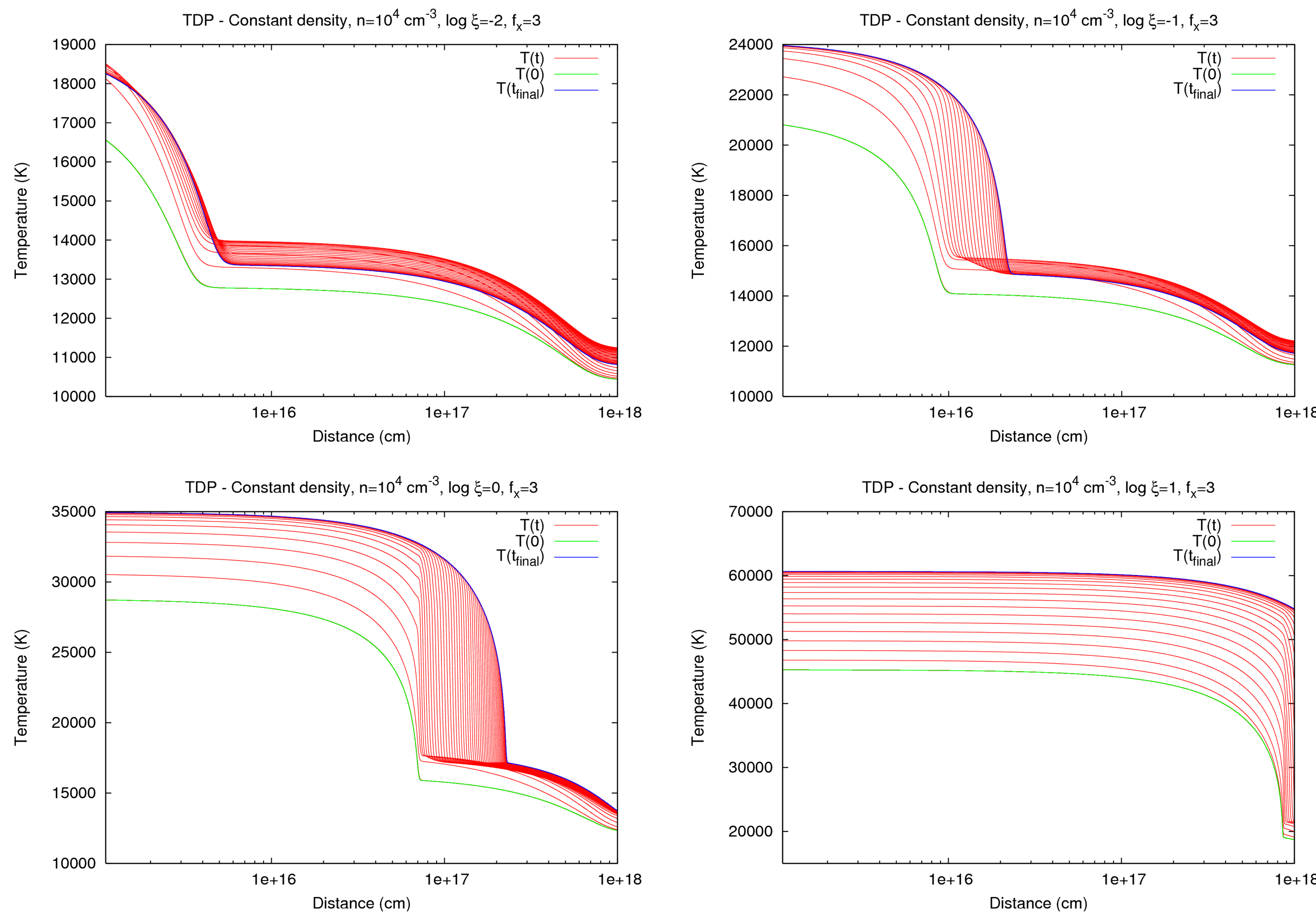
$$1/c\, dJ/dt + dJ/dR = -k J$$

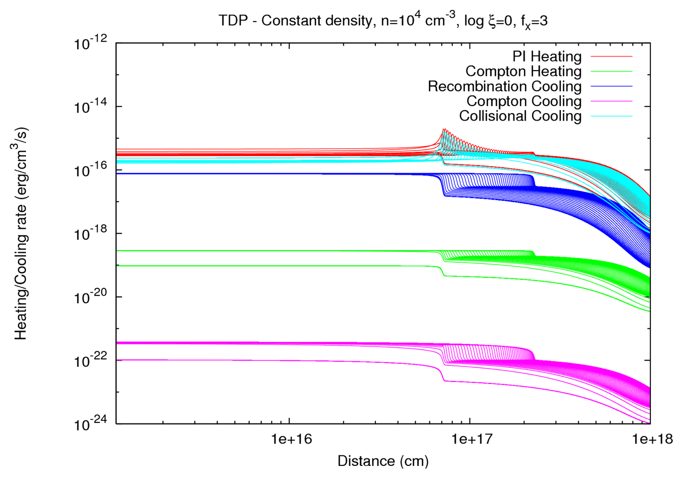
where J is the mean intensity of the radiation field, k is the opacity and c the speed of light. These 3 basic equations are then coupled and solved for each position R and time t. We use a finite-difference scheme to integrate the equations implementing the implicit method, given the large differences in the relevant characteristic times.

The spatial integration is performed in 1 dimension, thus we are considering a plane-parallel slab of gas that is s

Results – Constant Density

Simulations for the photoionization of a slab at constant density for different illumination fluxes. In all these cases the density is fixed at $n=10^4$ cm^{-3}, the radiation field is a power-law with photon index Γ=2, and composed of only hydrogen atoms. At a given time $t=10^7$ sec, the source flux is increased by 3 times its original value. We then follow the evolution of the gas temperature until the system returns to equilibrium.





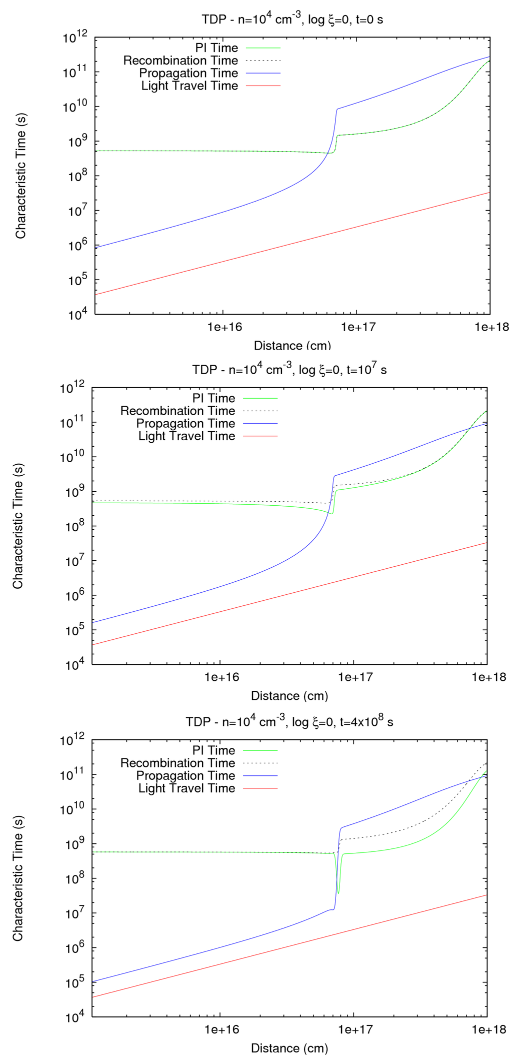
This Figure shows each one of the physical processes responsible for the heating or cooling of the gas, plotted along the distance *R* and for each time step.

The dominant process is the photoionization heating. In a pure H gas, radiative recombination is unable to control the heating. Thus, cooling due collisional excitation is needed to reach equilibrium again.

Compton heating/cooling plays a minor role in these simulations.

Results – Characteristic Times

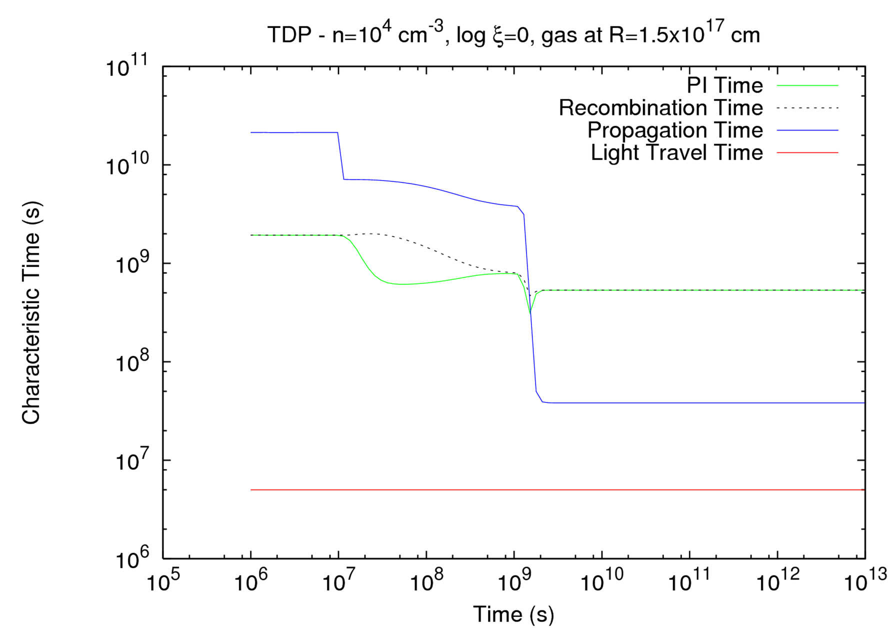
Since the temperature and the radiation field evolve with time at each point in the slab, then the different characteristic times are functions of both position and time. In the next 3 Figures we show the photoionization (PI), recombination, propagation and light travel characteristic times as functions of the distance *R* at 3 different times in the simulation.



- Equilibrium Solution at $t=0$ s. Initially the system is in equilibrium, thus the PI and recombination times (per particle) are the same. The propagation or **Stromgren time** is shorter for small distances, meaning that for that region the gas will be hot and ionized. At $R\sim7\times10^{16}$ cm gets longer than the PI and recombination times, letting the gas to cool down and become more neutral.

- Flux variation at $t=10^7$ s. The ionizing flux is increased by a factor of 3 as an step function. This causes a departure from equilibrium, which is evident near the interface between the ionized and the neutral zones. Since the flux is increased, the PI heating becomes more important, raising the temperature.

- Going back to equilibrium. At later times ($t>10^7$ s) after the flux variation, the departure from equilibrium moves deeper into the slab. However, the regions closer to the source are already getting to their equilibrium values, and that is why the PI and recombination times are equal for $R<10^{17}$ cm. Note that in all the cases the relevant times are **longer than the light travel time**.



In this Figure we follow the temporal evolution of the relevant characteristic times for one parcel of gas, located at $R=10^{15}$ cm from the source. It is clear that the departure from the equilibrium occurs right after the flux is increased ($t>10^7$ s), where the PI and recombination characteristic times diverge.

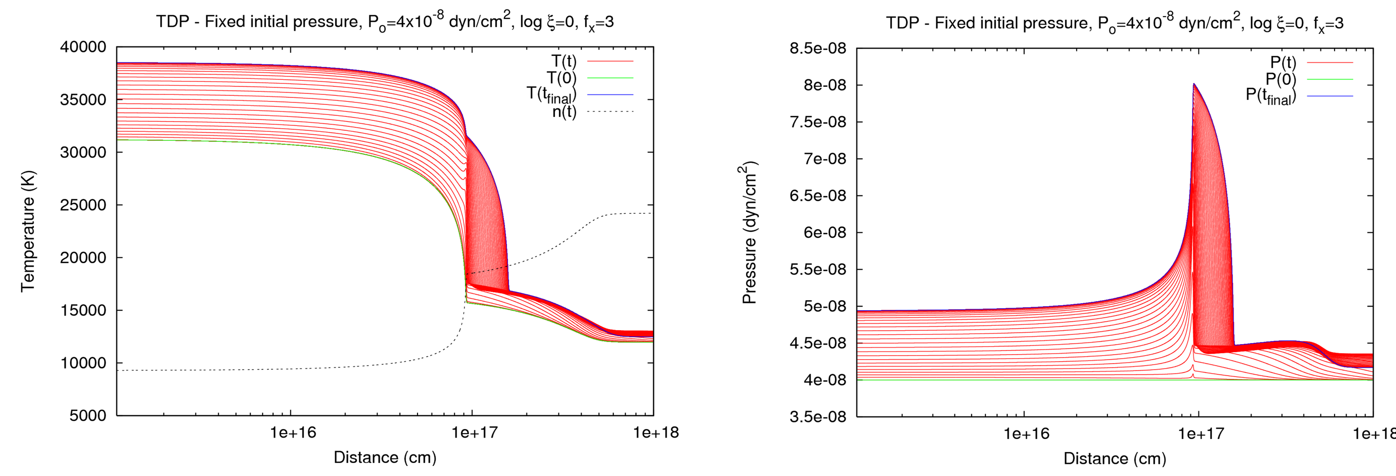
Equilibrium is not reached again until $t\sim10^9$ s, when the propagation time becomes shorter than the others.

Results – Fixed Initial Pressure

We have also carried out simulations in which the gas pressure is held fixed at one particular value ($P=4\times10^{8}$ dyn/cm^2) at the initial time. The equilibrium ($t=0$) solution is found, which provides a density profile. We then let the pressure to evolve with time, fixing the gas density to the profile obtained initially.

In the next two figures we show the resulting temperature (left) and pressure (right) profiles for this type of simulation. The gas density obtained from the equilibrium solution is shown in the left Figure as black dashed line. The ionization/recombination front found originally near $R\sim10^{17}$ cm is compensated by sharp increase in the density in order to keep the pressure constant.

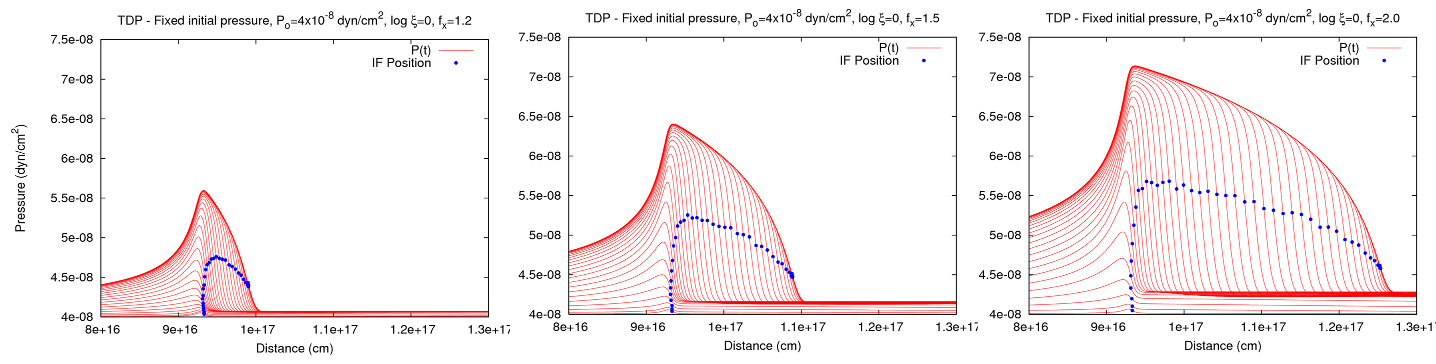
As the flux increases the front travels deeper into the cloud, heating the higher density region of partly ionized gas. This creates the big pressure spike where the front was located before.



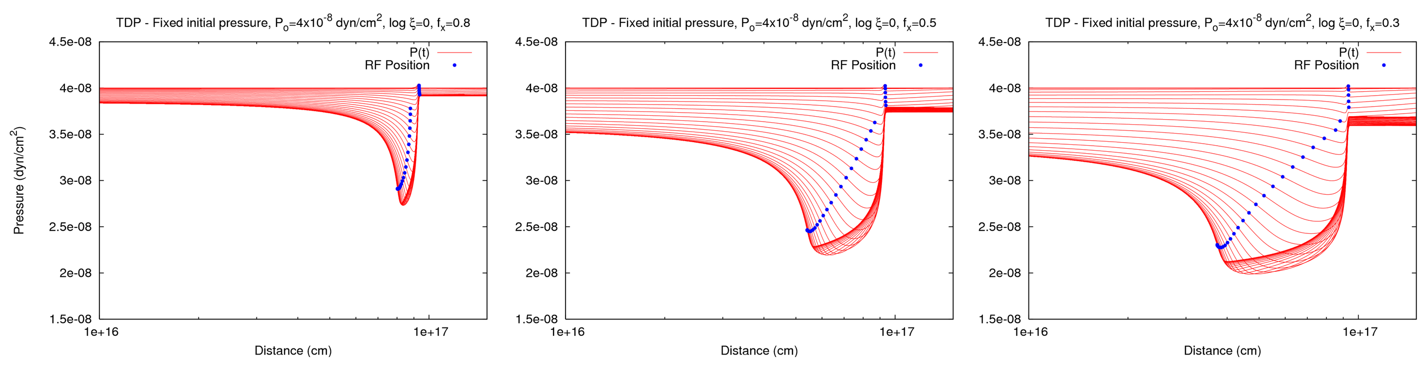
The presence of these fronts in the pressure profiles have important dynamic effects in the cloud. If the front travel subsonically, the cloud will adjust its density, but if the front is supersonic shocks will be created and the cloud will fragment.

Results – Ionization & Recombination Fronts

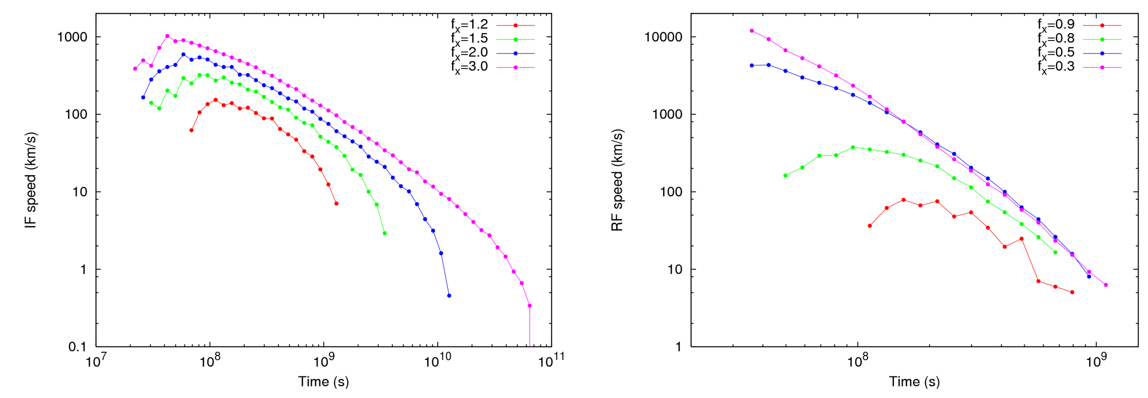
We also explore how the fronts propagate under different variations of the illumination source. The next 3 Figures show the pressure profiles in the region where an ionization front (IF) is formed for the cases where the flux is **increased** by factors of f_x*=1.2, 1.5* and *2*. The blue dots are the location of the front, determined by the inflection point in each curve (most negative value for *dP/dR*).



Conversely, recombination fronts (RF) are formed and propagate backwards if the original ionization flux is **decreased,** as it is show in the next 3 Figures, which correspond to decreasing factors of f_x*=0.8, 0.5* and *0.3.*



With these positions we can then derive the speeds at which the IF's or the RF's propagate thought the media. In the last two Figures, we show the speeds for the IF (left) moving forward deep into the cloud, and those for the RF (right) which propagate backwards, towards the source. Each curve corresponds to a different variation of the ionizing flux.



In general, we see ionization fronts moving up to speeds of 10^3 km/s over long periods of time. The recombination fronts seem to propagate at much higher speeds (10^4 km/s), but they live short times before the gas reaches equilibrium again.

Conclusions

[1] Lyu & Bruhweiler 1996;
[2] Joulain et al. 1998),
[3] Rodriguez-Gaspar & Tenorio-Tagle 1998;
[4] Richling & Yorke 2000
[5] Schmidt-Voigt & Koeppen 1987;
[6] Frank & Mellema 1994;
[7] Marten& Szczerba 1997
[8] Hauschildt et al. 1992;
[9] Beck et al. 1995
[10] Kozma & Fransson 1998
[11] Ikeuchi & Ostriker 1986;
[12] Shapiro & Kang 1987;
[13] Shapiro, Giroux, & Babul 1994;
[14] Ferrara & Giallongo 1996;
[15] Giroux & Shapiro 1996;
[16] Zhang et al. 1997).
[17] Dessart & Hillier 2008