Time-Dependent Photoionization Modeling of Gaseous Nebulae

Manuel Bautista[1], Ehab ElHoussieny[1], Javier Garcia[2], T.R. Kallman[4]
[1]Western Michigan University, [2]Harvard University, [3]NASA Goddard Space Flight Center

Abstract

Photoionized plasmas are the most commonly observed in astronomy, particularly through optical and UV observatories, such as the Hubble Space Telescope (HST). Modeling astronomical photoionized plasmas is generally done from the condition of steady-state statistical equilibrium, but none-equilibrium time-dependent photoionization (TDP) is found in a large variety of astronomical objects, yet it has received little attention thus far. There are multiple examples of notable failures of steady-state photoionization modeling. We have developed of a general purpose time-dependent photoionization modeling code and its use in the analysis of astronomical spectra. The new code, TDPX, is capable of including all chemical elements from hydrogen (Z=1) to nickel (Z=28). The code to the study of non-equilibrium conditions in FeLoBAL quasars and the BLR regions of AGNs.

Introduction

Potoionization modeling comprises any situation in which energy in the form of electromagnetic radiation is then re-processed by gas, which becomes ionized and heated, and the excess energy is re-emitted into longer wavelength spectral lines and diffuse continuum. Photoionized plasmas are the most commonly observed in astronomy, particularly through optical and UV observatories, such as the Hubble Space Telescope (HST). This is because photoionized plasmas expand through a huge range of temperatures and density conditions and are present in most, if not all, bright astronomical objects.

Thus far, modeling of astronomical photoionized plasmas is generally done from the condition of steady-state statistical equilibrium, which means that gas ionization is balanced by recombination, atomic excitations are balanced by spontaneous and induced de-excitations, and electron heating is balanced by cooling. There has been much progress in steady-state photoionization modeling in the last few decades and at present there are several photoionisation modeling codes in use.

The break down of the steady-state assumption is an intrinsic characteristic of many types of objects. For instance, time-dependent photoionization (TDP) modeling has been discussed in the interstellarmedium, H II regions, planetary nebulae, novae and supernovae, the reionization of the intergalactic medium, ionization of the solar chromosphere, Gamma ray bursts, accretion discs, active galactic nuclei (AGN), the evolution of the early Universe, and Broad Absorption Line (BAL) and Fe II low ionization BALs (FeLoBAL) quasars. However, TDP modeling in astronomy is in its very early stages.

Time-Dependent Photoionization Modeling

The steady-state assumption breaks down whenever variability period in either the ionizing radiation continuum or the geometrical structure of the plasma is short compared to the equilibration time scales for excitation, ionization, and thermal balance.

Figure 1 shows the equilibration times versus depth into the slab for a pure hydrogen cloud with $=10^4$ cm^{-3}. It is seen that fronts that result from sudden increases in the radiation flux travel at constant speed, ~20,000 $km.s^{-1}$, from the illuminated face of the cloud. Near the ionization front (IF), the propagation time increases non-linearly. It takes about 1 year for the radiation front to arrive near the IF, but hundreds of years to move across the IF. Thus, the IF expected to exhibit the largest departures from equilibrium conditions after changes in the ionizing radiation field.

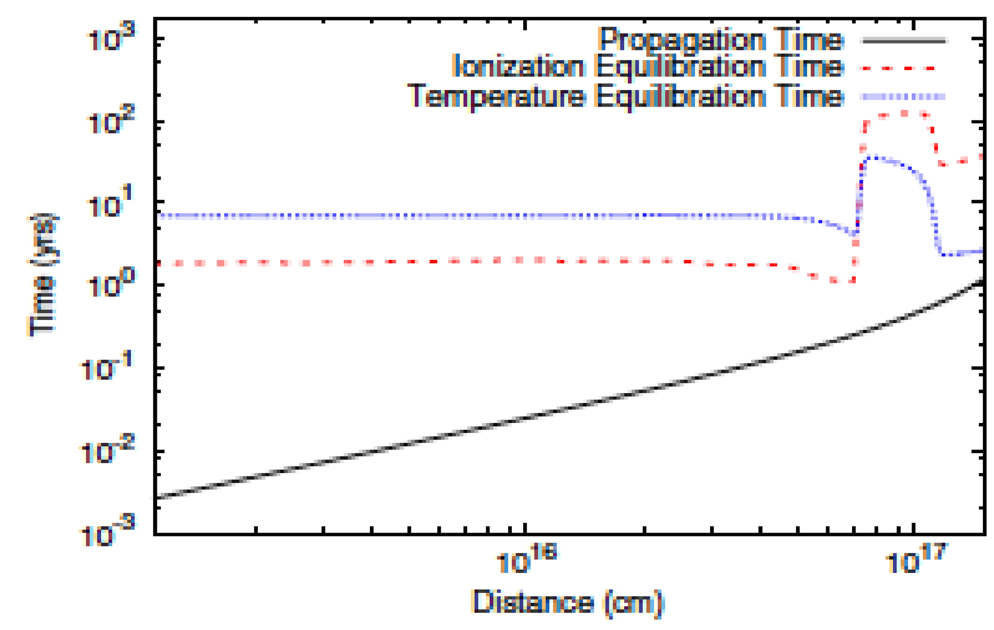

Figure 1. Equilibration time scales for a gas cloud with density 10^4 cm^{-3} subjected to a sudden increase in ionizing continuum by a factor of three

Figure 2 shows temperature and hydrogen ionization results for the same cloud modeled above, but with the addition of 10% of helium by number into the plasma mixture. Also, we use aperiodically varying radiation source with a period of 1 yr and amplitude of 50%. It can be seen that the physical conditions tend to oscillate between the two extreme equilibrium states, but with noticeable increasing delays between illuminated face of the cloud and the IF. This leads to propagation of heating and cooling waves through the cloud, thus a much more complex temperature structure than under equilibrium conditions. Toward the back of the cloud there is no one sharp IF, as expected in steady-state, but a very extended and double peaked transition region from fully ionized to mostly neutral gas.

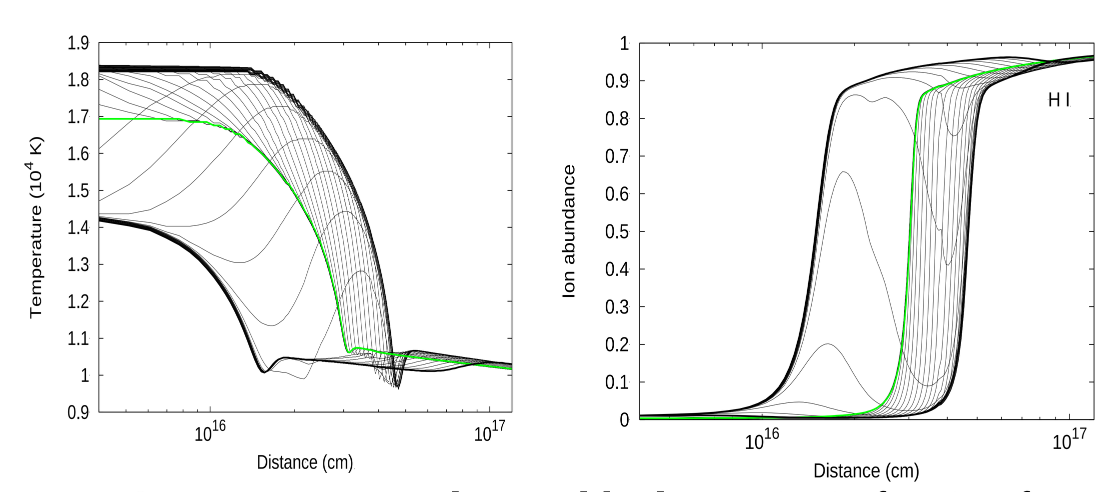

Figure 2. Temperature and neutral hydrogen ionic fraction for a cloud subjected to a periodically varying radiation source with a period of 1 yr and amplitude of 50%.

Time variability of the ionizing source leads to much more extended and complex ionization fronts than under steady-state conditions. This has a profound effect on the spectra from neutral and low ionization species. For instance, the ionic fraction of Fe II is shown in Figure 2. It is found that the variability of the ionizing continuum yields a very extended Fe II, as opposed to the very narrow region expected under steady-state conditions.

Time-Dependent Modeling of BAL Quasars

BAL quasars are of great interest in astronomy, owing to their important role in the undersanding of galactic evolution. Analysis of these observations through steady-state photoionization has led to estimated of mass outflows and kinetic luminosities, which would make major contributor to AGN feedback.

In general, BALs are not expected to be in steady-state equilibrium. These objects are characterized by drastic spectral variability on both the ionizing continuum and the structure of the absorption troughs on times scales shorter than equilibration time scales.

Figure 3 shows that the column density of Fe II could be up to orders of magnitude greater than in steady-state conditions. Thus, the steady-state assumption underestimates the ionization parameter of the outflow by several factors. This, in turn, has the effect of bringing the outflow closer to the ionizing source than currently estimated and reduce its calculated mass outflow and kinetic luminosity.

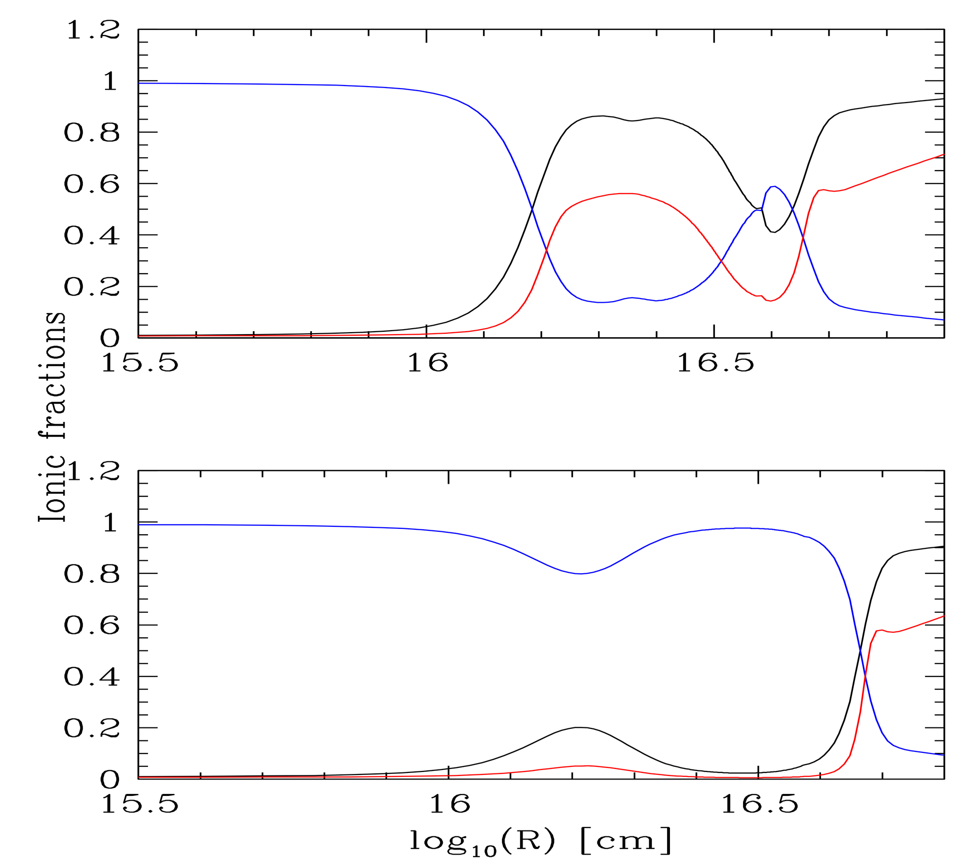

Figure 3. Ionization structure of H^+ (blue line), H^0 (black line), and Fe^+ (red line) across the ionization front. The simulation corresponds to a periodically varying radiation source with a period of 1 yr and amplitude of 50%. The two panels show the results at two different instants during the simulation.

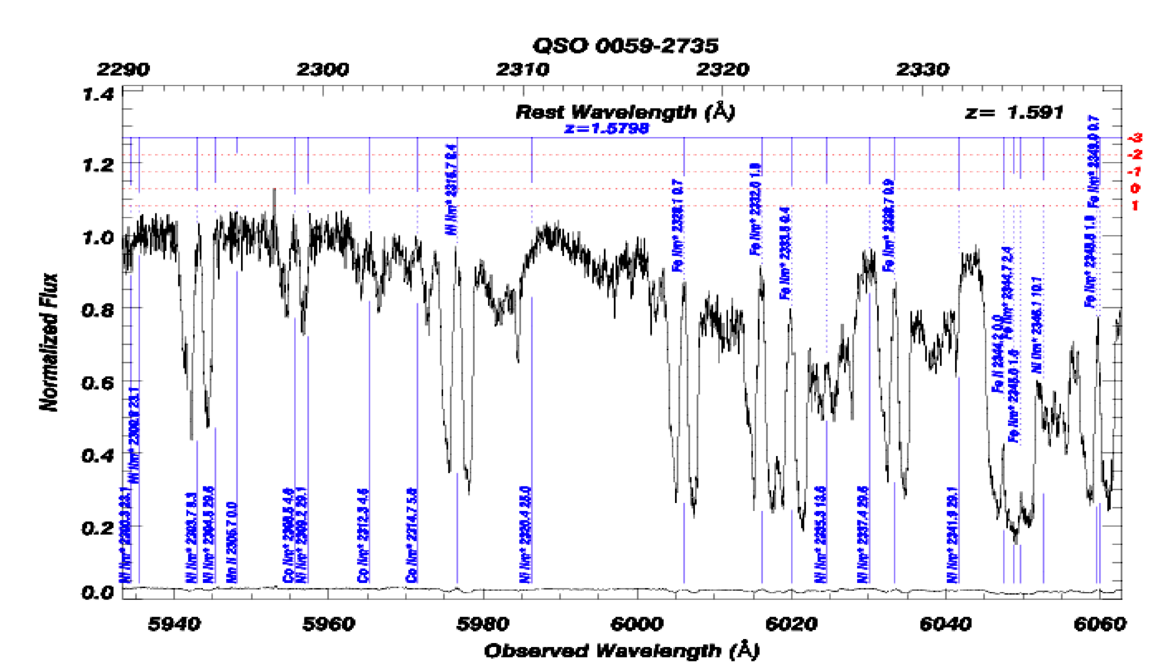

Figure 4. Spectra of BAL quasar taken with the Very Large Telescope (VLT). Several absorption troughs are identified, which result from outflowing winds from supermassive central black hole. The wind transports mass and energy from the black hole to the host galaxy, thus the wind constitutes an important feedback mechanism.

Conclusions

None-equilibrium time-dependent photoionization (TDP) is found in a large variety of astronomical objects, yet it has received little attention thus far. In absence of detailed TDP treatments, it has been assumed that the time-averaged photoionized spectrum is the same as the spectrum produced by the time-averaged ionizing continuum. However, this cannot be correct in detail, as we know that the response of the photoionized gas to changes in the ionizing source is highly non-linear. Further, there are multiple examples of notable failures of steady-state photoionization modeling.

We have developed the first general purpose modeling tool for such phenomena. We took the widely used modeling code XSTAR (Kallman and Bautista 2000) and extended the excitation, ionization, thermal, and radiative transfer equations to their full time-dependent forms. The new code, TDPX, is capable of including all chemical elements from hydrogen (Z=1) to nickel (Z=28). This work is the Ph.D. thesis of E. Elhoussieny.

At present, we are working on two specific goals:

- We are developing a version of the TDPX code to run on parallel computers. Then, the code can be made available to the general community.
- Applying the parallel TDPX code to the study of non-equilibrium conditions in BAL quasars and the BLR regions of AGNs. We will concentrate, particularly, on the spectra from species found across the IFs. It is expected that the spectra from such spectra will reveal the signatures of non-equilibrium ionization, hence providing valuable diagnostics.