Numerical Modeling Studies of X-ray Photoionization Experiments Driven by Z-Pinch X-rays

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Motivation

Many interesting astrophysical objects (AGN, XRBs) are photoionization-dominated: hard x-rays produced by accretion control the ionization, excitation, and spectral properties of the surrounding plasma. There is a need to benchmark codes and better understand the underlying atomic and spectral physics of these photoionized sources. **We are carrying out an experimental campaign at the Z-Machine at Sandia National Laboratory that aims to produce a well-characterized x-ray photoionized plasma.** By modeling the spectra of this laboratory plasma, we will benchmark codes that can then be used to model high-resolution x-ray spectra of astrophysical objects.

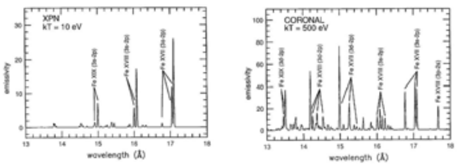


Fig. 1: Iron model emission rate spectra for a photoionized plasma (left) and a coronal plasma (right). Note how the different level-populating routes in the two cases lead to very different emission line intensities and also how overionized for its temperature the photoionized plasma is. Figures taken from Liedahl et al. *Ap. J.*, 350, L37 (1990).

Photoionized and collisional plasmas have very different spectral signatures.

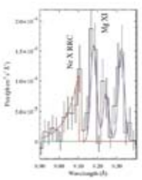
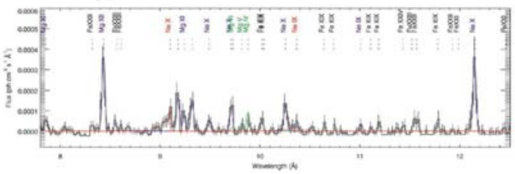


Fig. 2: High Resolution X-ray Spectrum of the stellar wind in the HMXRB Vela X-1.

Note that narrow radiative recombination continua (left and below), which are characteristic of photoionized plasma, are shown in red, fluorescent lines, which are also characteristic of photoionized plasmas, are shown in green, and highly ionized lines in blue (below).

Figure from Schulz et al. *Ap. J.*, 564, L22-L23 (2002)



Gas Cell Experiments

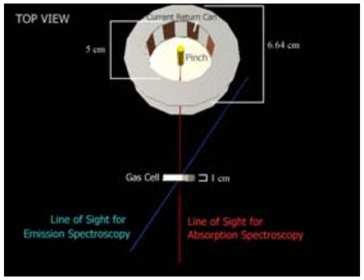


Fig.3: Top view schematic of our experimental set-up. A cm-scale neon-filled cell is mounted several cm from the x-ray emitting pinch. **The gas in the cell is analogous to the photoionized plasma in an x-ray binary system, and the pinch is representative of the x-ray emitting inner shell of the accretion disk.** We can measure spectra along various sight-lines through the pinch, for comparison with space-based measurements of cosmic plasmas and, especially, for confrontation with modeling.

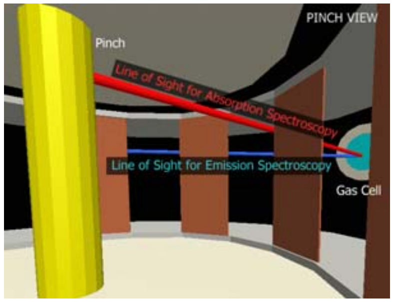


Fig. 4: View of the same experimental schematic from the position of the pinch (above). On the right, we show The Z Accelerator at Sandia National Laboratories banking its pulse-forming switches before a shot (top); the anode insert and current return can through which the current pulse passes after being driven through the Z-pinch wire array (middle); and a tungsten wire array which acts as the Z-pinch in the experiment (bottom).

The Z accelerator is the most powerful source of x-rays in the world, utilizing an imploding tungsten array to produce plasmas with an **x-ray power of 290 TW for an order 10 nanosecond pulse** which amounts to a total of 1.9 MJ for the entire pulse.

Experiments already completed have used neon of density $n_{ion} \sim 10^{18}$ cm^{-3} and an ionization parameter of ~5. We measured the neon spectrum in absorption (the pinch serves as the backlighter) with a time-integrated spectrometer. For future experiments, we plan to make simultaneous time-resolved emission and absorption spectroscopic measurements.

The absorption spectra, via their K-shell features, provide information about the ionization distribution in the plasma, while the emission spectra provide temperature information (via the widths of narrow RRCs) and show the same recombination cascades that are seen in astrophysical sources.

Because we know the ionizing spectrum and the gas properties (e.g. density), the simultaneous absorption and emission spectra observed in future experiments should provide a stringent test of codes used to model photoionized plasmas.

Modeling the Experiments

In order to understand the experimental results and properly test the atomic and spectral models against the observed spectral data, we must perform a series of simulations: (1) A view-factor calculation to determine the time- and wavelength-dependent x-ray flux onto the neon gas cell; (2) A non-LTE hydrodynamics calculation to determine the time-dependent plasma and radiation properties within the cell; and (3) A non-LTE level population and spectral synthesis calculation to model the observed spectra.

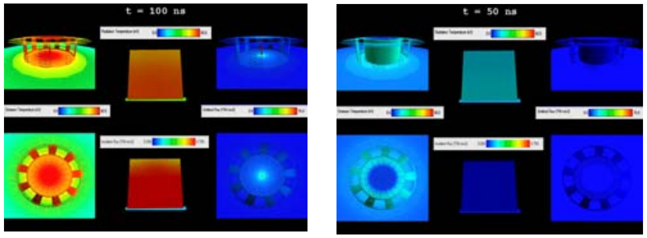


Fig. 5: Two snapshots from *VisRad* view-factor simulations of the gas cell experiment.

The left image is an earlier time in the simulation during the low temperature foot of the pinch emission, and the right image is a later time from the high-temperature peak. In each image, the right and left columns depict the Z machine diode/pinch assembly, and the center column depicts the face of the gas cell.

The viewfactor simulation output (see Fig. 5) is used as input for the non-LTE hydrodynamic simulation, using the 1-D Lagrangian code, *Helios*, we show the temperature and density distributions within the cell as a function of time.

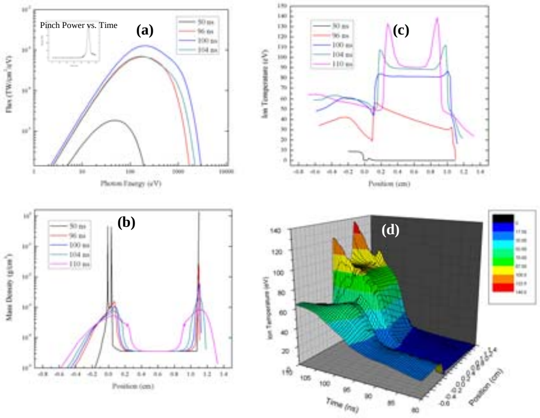


Fig. 6: (a) Time-dependent incident flux at the center of the face of the gas cell (with the pinch power vs. time inset), (b) mass density as a function of position in the gas cell for several times in the hydro simulation, (c) ion temperature as a function of position for several times in the simulation, and (d) a 3-D plot of ion temperature as a function of position and time.

In the hydro plots (b, c, d), the radiation field is incident from the left. Note the shock heating due to the collapse of the mylar walls of the gas cell and compression of the gas in (b), and the radiation wave evidenced by the temperature gradient for earlier times in (c) and (d).

In the final step of the simulation process, the non-LTE statistical equilibrium code, *Spect3D*, uses the *Helios* output and inputs atomic level structure and transition rates to synthesize time-resolved absorption spectra, which we compare with experimental data, below. Note the many components of the He-like n $\rightarrow$ 2 series, which are generally very well matched in our simulation.

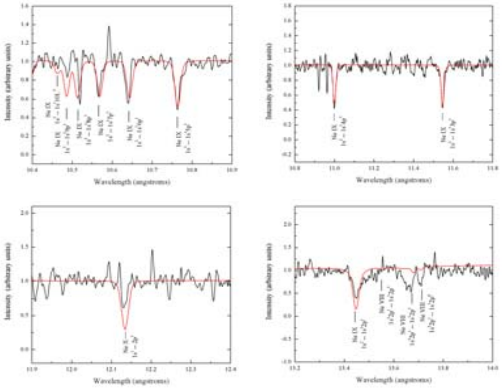


Fig. 7: Spect3D synthesized spectrum (red) matched to the measured time-integrated absorption spectrum from Shot Z543 (black). The spectral resolution of the synthesized spectrum is E/dE = 800.

Our simulation process also can produce time-dependent absorption and emission spectra, which will be compared to data from experiments we plan to carry out next year. Future experiments will also have different gas fills (e.g. argon) and lower densities and different gas cell configurations, which should enable us to reach ionization parameters of several hundred.

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Copies of this poster and related information can be obtained from `www.swarthmore.edu/~cohen/projects/gas_cell/`