Laboratory Generated Photoionization Fronts Relevant to Cosmology

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Abstract

Photoionization Fronts (commonly referred to as Ionization Fronts or PI fronts) are a type of radiation-driven heat front that dictate important physics in the reionization era of the early universe. The first galaxies of the reionization era merged to form minihalos. Subsequently, these minihalos emitted ionizing radiation to the surrounding gas clouds, which generated PI fronts. The asymmetric propagation and attenuation of a PI front within a gas cloud is an active area of study in the early universe cosmology. In the laboratory setting, the Z Astrophysical Plasma Properties (ZAPP) platform on Sandia's Z-Machine facility is capable of generating an intense radiation source to drive a PI front through a 0.75 atm nitrogen gas cell. To better understand upcoming ZAPP experiments on Sandia's Z-Machine, this work presents an initial experimental design, accompanied by HELIOS radiation-hydrodynamic simulations, and PrismSPECT atomic kinetics calculations.

Astrophysics Motivation

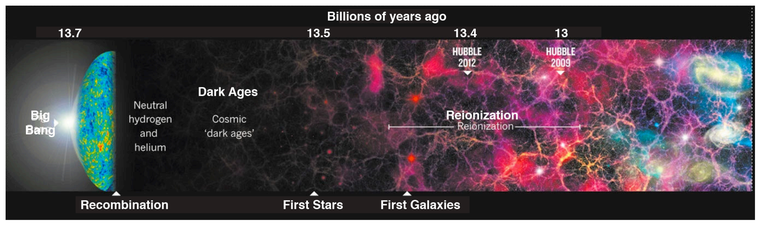

Figure 1. History of Universe[1]

Reionizaiton Era

- **Dark matter Mini-halo's emit ionizing photons into the surrounding intergalactic medium during the Reionization Era**

$$\frac{dn_{ion}}{dt} = f_{esc}\zeta_Q\rho_{SFR}$$

- **[1]The production rate density of ionizing photons (n_{ion}), is proportional to the the escape fraction (f_{esc}), number of photons emitted per star(ζ_Q), and star formation rate (ρ_{SFR})**
- **The escape fraction of photons moving through a PI front help determine when the Reionization Era occurred**

Detection of High Redshift Galaxies

- **[2]Shifts in the Lyman and Balmer spectral lines from high redshift (~z = 6) galaxies can be used to determine age**
- **Metals in the interstellar medium can greatly effect the measurement of the Lyman and Balmer shifts and the resulting galaxy age (~z $\pm$ 3)**
- **Measurement of the downstream line emission spectra from metal enriched PI fronts can reduce the uncertainty in galactic age**

CLASP CLIMATE & SPACE Sciences & Engineering

Experimental Design

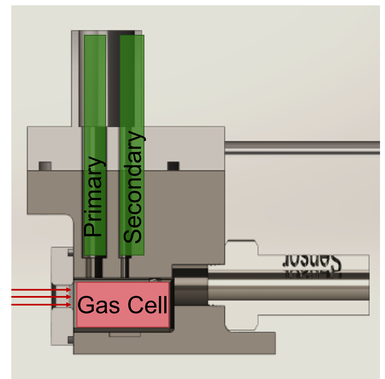

Figure 2. Gas Cell CAD

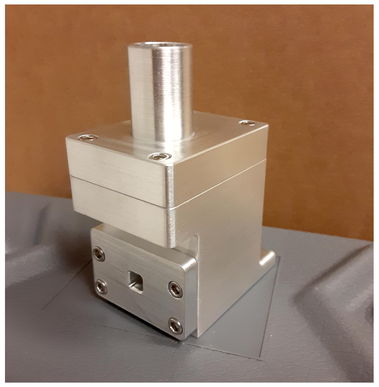

Figure 3. Gas Cell as Built

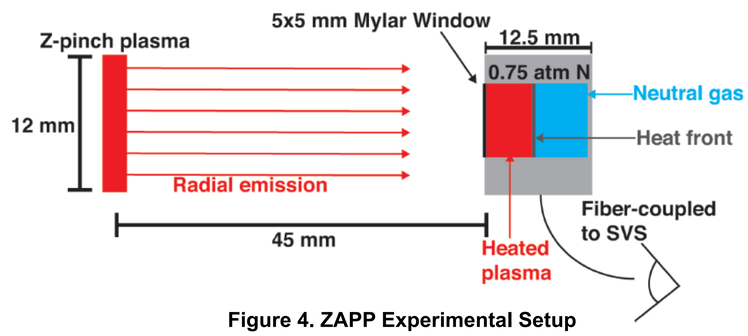

Figure 4. ZAPP Experimental Setup

Photoionization Fundamentals

- **Euler Equation: Flux conservation across the PI Front**
- **Mass:** $\rho_1 u_1 = \rho_2 u_2$
- **Momentum:** $\rho_1 u_1^2 + p_1 = \rho_2 u_2^2 + p_2$
- **Energy:** $\left(\frac{\rho_1 u_1^2}{2} + \frac{\gamma p_1}{\gamma - 1}\right) u_1 - F_R = \left(\frac{\rho_2 u_2^2}{2} + \frac{\gamma p_2}{\gamma - 1}\right) u_2$

Key Predictions

- **Radiation flux from Sandia Z-Machine will drive a PI front within the nitrogen gas cell**
- **The PI front velocity will be ~2,100 [km/s] and traverse the 12.5mm gas cell in ~ 6.5ns**
- **The PI front will be a supersonic heat front and cause a spike in electron temperature. There will be no shock (hydrodynamic motion) so the density will remain unchanged**
- **The nitrogen gas will reach approximately the third ionization state (NIV)**

Photon Doppler Velocimetry (PDV)

- **Will use perpendicularly-mounted PDV as a shock arrival measurement**
- $v_{PI\,front} \cong 2,131\frac{m}{s}$; $v_{e-front} \cong 291\frac{m}{s}$
- **Future goal of using 2 PDV to front velocity measurement**

Streaked Visible Spectrometer (SVS)

- **Primary diagnostic to determine the temperature and density**
- **Will utilize spectral line ratios to characterize plasma and determine ionization state distribution**

Simulated Line Emission

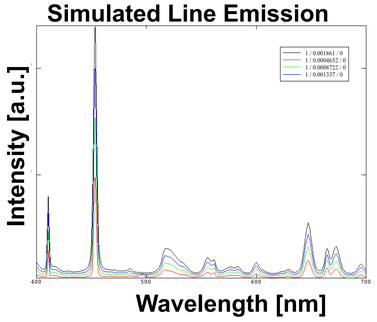

Figure 5. Simulated Line Emission of Nitrogen

Simulated SVS Signal

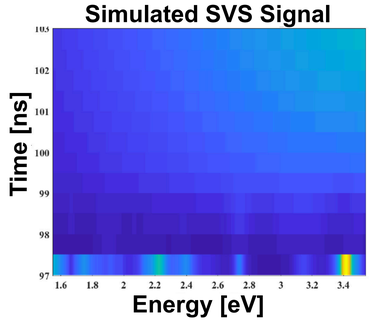

Figure 6. Simulated SVS Signal

Wavelength [nm]	Intensity	Probe
410.8	Standard	Density
454.3	**Strong**	**Density / Temperature**
522.1	Standard	Temperature
647.4	Weak	Temperature

Future Work

- **Establish PI front experimental platform on Sandia Z-Machine**
- **Field ZAPP experiments in July of 2021**
- **Use nitrogen filled gas cell to collect SVS and PDV signal**
- **Make a PI front velocity measurement**

Acknowledgments/References

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