Far Ultraviolet Spectroscopy of a Nonradiative Shock in the Cygnus Loop: Implications for the Postshock Electron-Ion Equilibration

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Abstract. We present far ultraviolet spectra of a fast (\(\sim 300 \text{ km s}^{-1}\)) nonradiative shock in the Cygnus Loop supernova remnant. Our observations were performed with the Far Ultraviolet Spectroscopic Explorer (FUSE) satellite, covering the wavelength range 905–1187 Å. The purpose of these observations was to estimate the degree of electron-ion equilibration by (1) examining the variation of O VI \(\lambda\lambda 1032, 1038\) intensity with position behind the shock, and (2) measuring the widths of the O VI lines. We find significant absorption near the center of the O VI \(\lambda\lambda 1032\) line, with less absorption in O VI \(\lambda 1038\). The absorption equivalent widths imply an O VI column density greatly exceeding that of interstellar O VI along the Cygnus Loop line of sight. We suggest that the absorption may be due to resonant scattering by O VI ions within the shock itself. The widths of the O VI emission lines imply efficient ion-ion equilibration, in agreement with predictions from Balmer-dominated spectra of this shock.

INTRODUCTION

A shock wave is termed nonradiative if the cooling time of the postshock gas exceeds the dynamical time scale. Nonradiative shocks lack cooling zones, therefore the optical and ultraviolet line emission is excited close to the shock front. The emission line fluxes and line widths are sensitive to the shock velocity and the degree of postshock electron-ion/ion-ion equilibration. This property makes the optical and ultraviolet lines valuable tools for investigating collisionless heating in high Mach number, low density shock waves.

For an ion of mass \(m_i\), the jump conditions for a strong shock in an ideal gas medium (\(\gamma = \frac{5}{3}\)) give a postshock temperature

\[T_i = \frac{3}{16} \frac{m_i V_s^2}{k}\]  \hspace{1cm} (1)
In an unequilibrated shock, the electron and proton temperatures are in the ratio $1/2000:1$, while the temperatures of O ions and protons are in the ratio of $16:1$. In contrast, the temperatures of all three species are equal in an equilibrated shock. Collisionless heating can produce equilibrations anywhere between these two extremes. In principle, the amount of collisionless heating from plasma waves, MHD turbulence and other processes is sensitive to such parameters as the magnetosonic Mach number and angle between the magnetic field and shock front. Understanding this relationship is of critical importance in the interpretation of X-ray, ultraviolet and optical data of high Mach number collisionless shocks.

A nonradiative shock in partially neutral gas emits a pure Balmer line spectrum generated by collisional excitation. Each Balmer line consists of a narrow component produced by excitation of cold H I and a broad component produced by proton-H I charge exchange. The shock velocity and electron-ion equilibration can be gauged from the broad component line width and ratio of broad component to narrow component flux [1] [2]. The ion-ion equilibration can be gauged in turn by measuring the width of the O VI $\lambda\lambda1032, 1038$ lines and the variation of O VI flux with position behind the shock.

**OBSERVATIONS**

The target of our FUSE observations was Cygnus P7, a nonradiative shock in the NE corner of the Cygnus Loop supernova remnant [1]. We acquired ultraviolet spectra of Cygnus P7 in June 2000 for a total of 64 ks (all during orbital night) and four slit positions behind the shock (Fig. 1). The spectra presented here were acquired through the $4'' \times 20''$ medium resolution (MDRS) slit. Slit position 1 was
centered on the crisp Balmer-dominated filament and placed parallel to it (Fig. 1). To observe the intensity variation of O VI, we centered slits 2, 3 and 4 at 5″, 10″ and 15″ behind the shock, respectively. The one-dimensional spectra of Positions 1, 2, 3 and 4 appear in Fig. 2. To minimize the background contribution, these spectra were extracted from the LiF 1A channel (one of four available with FUSE), the detector yielding the highest effective area at \( \lambda > 1020 \) Å. The spectral resolution is 0.08 Å(25 km s\(^{-1}\)), corresponding to filled slit emission.

### ANALYSIS

The 1-D spectra of Cygnus P7 (Fig. 2) reveal three important features: (1) The O VI lines are considerably broader than the airglow lines, confirming the detection of O VI emission in the Cygnus P7 shock. The velocity width of the O VI \( \lambda 1032 \) line is \( \sim 120 \) km s\(^{-1}\). Combining this result with the shock velocity of 300–365 km s\(^{-1}\)predicted from Balmer line spectroscopy of Cygnus P7, we obtain \( T_e/T_O \sim 0.7 \). This is roughly consistent with the electron-proton equilibration \( T_e/T_p \sim 0.7–1.0 \) predicted by the Balmer line analysis; In an earlier analysis [1] of Balmer line emission from Cygnus P7, we measured an H\( \alpha \) broad component width of 262 km s\(^{-1}\). This corresponds to a shock velocity of 265–365 km s\(^{-1}\) for cases of no equilibration and full equilibration, respectively. (2) the O VI emission lines are strongly affected by absorption. The absorption features tend to shift blueward at slit positions farther and farther behind the shock. The variation of O VI flux with position is masked by the O VI absorption features; (3) the shape of the \( \lambda 1038 \) absorption profile differs from that of the \( \lambda 1032 \) profile. This is mainly due to galactic H\( _2 \) absorption at the position of the O VI \( \lambda 1038 \) line.
There are two possible explanations for the observed O VI absorption: either the bulk of the absorption is produced by interstellar matter (O VI, H2, C II*, etc.) along the line of sight, or the absorption is produced locally by O VI ions within the shock. There are three lines of evidence in favor of the latter interpretation:

(1) The velocity width of the O VI λ1032 absorption feature is \( \sim 90 \) km s\(^{-1}\), comparable to the width of the λ1032 emission line. The O VI column density and temperature required to produce the observed absorption are \( N_{O \, VI} \gtrsim 2 \times 10^{14} \) cm\(^{-2}\) and \( T_{O \, VI} \sim 3 \times 10^6 \)K. These values are \( \gtrsim 10 \) times larger than the O VI column density and temperature expected for the ISM along the Cygnus Loop line of sight [3]. (2) The progressively larger blueshift of the O VI absorption lines with distance behind the shock cannot be explained by interstellar O VI absorption. (3) The line center ratio \( I_{1038}(v=0)/I_{1032}(v=0) \) varies significantly with slit position, from around 0.6 (Position 2) to 1.1 (Position 4). These localized variations are consistent with O VI resonant scattering within the shock.

The appearance of the O VI spectrum may be due to a combination of internal resonant scattering and a curved shock geometry. On the one hand, the O VI column density and temperature obtained from the FUSE spectra are consistent with the range of shock velocities (300–365 km s\(^{-1}\) from the Balmer lines) and preshock densities (\( n \sim 0.1–0.3 \) cm\(^{-3}\) from ROSAT X-ray observations) estimated for Cygnus P7. On the other hand, a curved shock geometry could explain both the increasing value of \( I_{1038}(v=0)/I_{1032}(v=0) \) and the increasing absorption blue shift with position behind the shock. In a curved shock, O VI photons produced farther downstream could be absorbed by O VI ions on the near (blue shifted) side of the shock.

**CONCLUSIONS**

In FUSE observations of a nonradiative shock in the NE Cygnus Loop, we find O VI emission line widths consistent with moderate to high electron-ion equilibration. We also find strong O VI absorption near the centers of the O VI emission lines. A quantitative explanation of the interplay between the O VI emission and resonant scattering requires (1) a careful modeling of the shock geometry, and (2) a Monte Carlo simulation to adequately treat resonant scattering at moderate optical depths (\( 0 \leq \tau \leq 1 \)). We will address these issues in future work.

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