Far Ultraviolet Observations of the High Mass X-ray Binary 4U1700-37/HD153919

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Abstract. The high-mass X-ray binary 4U1700-37/HD153919 has been observed with FUSE to study the effect of the X-ray source on the stellar wind of the primary. Phase dependent changes in the wind lines have been observed, indicating the creation of a X-ray ionization zone in the stellar wind. The X-ray luminosity of 4U1700-37 ionizes much of the wind and leaves a Stromgren zone. This disrupts the resonance-line acceleration of the wind in portions of the orbit, quenching the wind and disrupting the mass flow. This effect was found for the first time in 4U1700-37. This so-called Hatchett- McCray (HM) effect had been predicted for 4U1700-37, but was not previously detected.

1. Introduction 4U1700-37/HD153919

High-mass X-ray binaries (HMXRB’s) represent one of the key evolutionary paths for massive stars and are unique laboratories of stellar evolution. HMXRB’s are critical to our understanding of supernovae and the formation of neutron stars and black holes. HD 153919/4U1700-37 stands out as having the most massive and luminous primary of any HMXRB.

4U1700-37 has an O6.5 Iaf primary in a 3.412-day orbital period with a neutron star or black hole secondary (Rubin et al., 1996). The primary eclipses the compact object for about 25% of the binary period. The system is believed to have escaped from Sco OB I about 2.5 million years ago. The most recent mass estimates are those by Clark et al. (2002), who found $M_1 = 58M_\odot$ and $M_2 = 2.4M_\odot$. No X-ray or radio pulses or other periodicities are known, however RXTE All Sky Monitor and CGRO BATSE data show evidence of a 13.8-day periodicity (Hong & Hailey 2004). The primary slightly underfills its Roche lobe (Conti 1978), so accretion of the stellar wind onto the compact object powers the X-ray source. The X-ray light curve shows long eclipses and strong flaring behavior of which the physical origin is not known. X-ray pulsations have, however, not been detected, so that the nature of the compact object is unclear. As a consequence, the orbital and other fundamental parameters of the system (e.g. masses of both components) usually derived from X-ray pulse timing analysis are not accurately known.

This HMXRB system is unique in showing Raman-scattered emission lines in its UV spectrum (Kaper et al. 1990). These lines originate from strong EUV
emission lines in the spectrum of the X-ray source which are Raman-scattered to UV wavelengths by He II ions in the stellar wind. In this way, emission lines in the X-ray spectrum can be detected in the UV. Studies using IUE spectra of HD 153919 have found two surprising properties of HD 153919. There are a series of broad emission lines (Δλ = 2-3 Å) in the 200 Å centered on about 1650 Å that vary with orbital phase. These were shown to be Raman scattering of extreme UV photons (λ ∼ 255 Å) from the X-ray source by He II ions in the stellar wind (Kaper et al. 1990). The Raman lines appear and disappear with the binary phase, with maximum flux at phase 0.5 and minimum at phase 0.8. Raman scattering, a process in which the absorption of a photon is immediately followed by re-emission of a photon at a different λ (see Nussbaumer et al. 1989), is important in high temperature plasmas. [Rayleigh scattering is a special case of this process where the absorbed and emitted photons have the same λ.]

The Hatchett-McCray effect (Hatchett & McCray 1977), the phase dependence of the stellar wind resonance lines due to X-ray ionization of the wind, has been observed in Vela X-1, SMC X-1, and other HMXRB. The H-M effect was expected for HD153919, but not observed (Kaper et al. 1993). Similarly, no effect of the X-rays on the photospheric lines were found in IUE spectra (van Loon et al. 2001). The stellar wind and O star UV spectrum appear to be unaffected by the X-ray source (Clark et al. 2002)

2. FUSE Observations of 4U1700-37/HD153919

The stellar wind diagnostics in the far ultraviolet (FUV) are a unique source of information about the winds of massive stars. Unlike the main wind lines in the UV longward of Lyman-α (NV 1238-42, SiIV 1394-1402 and CIV 1548-50), the wind features in the FUV probe higher ionization states (OVI 1032-38) and the dominant ionization stages of the wind with species of lower cosmic abundance (SIV 1062-73, P V 1117-28) so the resonance lines are unsaturated (e.g. Massa et al. 2003).

4U1700-37 was observed by the Far Ultraviolet Spectroscopic Explorer (FUSE) at the four quadrature points of the binary orbit in 2003 April and August. The exposure times were ∼ 4 ksec at each orbital phase, producing high signal-to-noise spectra covering 900-1180 Å with a spectral resolution of 0.05 Å with S/N >30. The data were processed with latest FUSE calibration pipeline (CalFUSE v. 3.0.7). Figure 1 shows line profiles of several FUV wind lines on a velocity scale for two orbital phases, phase 0.49 (X-ray source conjunction) and phase 0.71 (near elongation). The S IV, P V, and Si IV lines are weakest at phase 0.49 and strongest at phase 0.71.

Figure 2 further illustrates the phase dependence of the S IV 1062 line by plotting all four phases, showing that these P-Cygni lines are strongest at the line center at phase 0.71 and weakest at phase 0.49. P V shows the identical behavior. The CIII 977 line is shown at the four orbital phases in Fig. 3. CIII is a trace species in the wind of an O 6.5 supergiant, since C IV is the dominant ionization stage of carbon. Even so, much of the CIII line profile is saturated (and also contaminated by interstellar Lyman-γ). The high velocity edge of the CIII profile is clearly visible, however, and is very similar to SIV. This phase dependence is consistent with that predicted for the HM effect in 4U1700-37
by Hatchett & McCray (1977). It was never found in longer wavelength lines because saturation masked the phase dependence. The H-M effect has been observed for the first time in 4U1700-37, 27 years after its prediction.

There is also evidence that the phase dependence of the different ions is a function of velocity in the wind. The P V 1118-1128 and S IV 1063-1073 P-Cygni lines are weakest at $\phi = 0.49$ and strongest at $\phi = 0.71$ for the red wing and at $\phi = 0.0$ for the blue wing (see Figure 1). There is also a small variation in the terminal velocity.

Figure 1. Stellar wind line profiles in 4U1700-37 at orbital phases 0.49 and 0.71 are shown on a velocity scale. The narrow absorption features are interstellar, primarily Lyman band transitions of H$_2$. 
The higher ionization lines, on the other hand, have a very different phase dependence. O VI 1038 and S VI 933-44 wind lines show orbital modulation different from P V and S IV and are strongest at $\phi = 0.5$ and weakest at $\phi = 0.0$ (X-ray source eclipse), implying that O VI and S VI are byproducts of the wind’s ionization by the X-ray source. Such variations were not observed in N V, Si IV and C IV because of their high optical depth. The P V and S IV transitions, on the other hand, are excellent tracers of the ionization conditions in the O star’s wind. P V is the dominant ionization stage in the wind and has lower cosmic abundance than C, N or Si. There is a small change in the terminal velocity ($v \sim 2000 \pm 200$ km/sec) of the wind with phase. The enhancement of O VI is not consistent with HM, and indicates that the production of O$^{+5}$ ions is closely connected with proximity to the X-ray source. S IV and P V are removed from the wind at the same orbital phases as O VI is produced. The modeling of the P-Cygni profiles with a modified version of the Sobolev Exact Integration method, as described in van Loon et al. (2001), is in progress.

Figure 2. P-Cygni profiles of the S IV 1062.662 line at the four quadrature points of the binary orbit.
Figure 3. The C III 977.020 resonance line is shown as a function of orbital phase.

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