Wind variability in early-type stars

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Chapter 11

Spectroscopic evidence for photo-ionization wakes in Vela X-1 and 4U1700-37

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Abstract

We present high-resolution, high signal-to-noise spectra of HD77581 and HD153919, the optical counterparts of the high-mass X-ray binaries Vela X-1 and 4U1700-37, respectively. The spectral lines show in unprecedented detail changes related to the presence of the X-ray source. For HD77581, at inferior conjunction of the neutron star an extra absorption component appears in the blue wing of the absorption lines. This feature first increases in strength (up till binary phase $\phi = 0.6$) whereafter it slowly decreases; at the same time it shifts more towards the blue. The observed velocities are low: from $-50$ km s$^{-1}$ at $\phi = 0.5$ up to $-250$ km s$^{-1}$ at $\phi = 0.8$. For HD153919, the observed variations are similar in character, but stronger and more complicated. For both systems we find significant variations in the P Cygni emission of the same lines, which are orbit dependent.

Based on the phase dependence of the velocity and strength of the absorption component, we show that it is unlikely that this component is related to an accretion wake, or to a gas stream through the inner Lagrangean point. We suggest that this component results from the presence of an X-ray induced photo-ionization wake in the system, trailing the X-ray source in its orbit. Furthermore, variations in X-ray luminosity most probably induce changes in the geometrical structure of the photo-ionization wake which may explain the observed orbit-to-orbit variations.


Based on observations obtained with the CAT/CES combination at ESO, La Silla, Chile
11. Photoionisation wakes in HMXRBs

1 Introduction

The stellar wind of OB supergiants, which provides the mass flux to power the X-ray source in high-mass X-ray binaries (HMXRB) such as Vela X-1 and 4U1700-37, is driven by the transfer of momentum from continuum photons, emitted by the supergiant, to the plasma via scattering and absorption in numerous spectral lines formed in the stellar wind. These lines are concentrated around the maximum of the spectral energy distribution of the OB supergiant, i.e. in the extreme ultraviolet wavelength region. This acceleration mechanism of the wind can be influenced by the X-rays originating from the compact object, since these will enhance the degree of ionization in its surroundings. Inside this Strömgren zone the radiative acceleration is quenched because for this highly ionized plasma most spectral lines are at X-ray wavelengths, and cannot support the acceleration of the flow (MacGregor & Vitello 1982). Collisions between the radiation-driven wind and the stagnant, highly ionized plasma will result in strong shocks and create dense sheets of gas trailing the X-ray source (Fransson & Fabian 1980).

Two-dimensional hydrodynamics calculations by Blondin and co-workers (1990, 1991), in which many effects influencing the wind dynamics around the compact object (gravitation, radiative acceleration, photo-ionization, X-ray heating/cooling etc.) are included, predict the formation of an accretion wake consisting of dense filaments and, depending on the separation of the objects, the presence of a tidal stream in the system. For high X-ray luminosities an X-ray induced shock (the so-called photo-ionization wake) at the border of the Strömgren zone dominates the accretion flow and trails the X-ray source in its orbit.

Evidence for X-ray photo-ionization of wind material in HMXRBs has been inferred from the orbital variations of the strong P Cygni lines in their UV spectra (e.g. Dupree et al. 1980, Hammerschlag-Hensberge 1980), an effect predicted by Hatchett & McCray (1977). When the X-ray source moves in front of the supergiant, the amount of blue-shifted P Cygni absorption diminishes, indicative of a Strömgren zone around the compact star. Furthermore, X-ray observations show an increase in X-ray hardness ratio towards late orbital phases (Mason et al. 1976, Haberl et al. 1989, and Haberl & White 1990). The emitted soft X-rays are thought to be (partly) absorbed by the accretion wake and/or the tidal stream obscuring the line of sight towards the X-ray source at late orbital phases. The change in strength of Raman-scattered emission lines in UV spectra of HD153919 with binary phase is consistent with the X-ray observations (Kaper et al. 1990).

Optical spectra of bright HMXRBs have revealed enhancements in blue-shifted absorption in strong spectral lines during and after the passage of the compact object through the line of sight towards the supergiant. Wallerstein (1974), Zuiderwijk et al. (1974), and Bessell et al. (1975) published Hα spectra of HD77581 showing periodic changes in this blue-shifted absorption. Zuiderwijk (1979) reported that an extra absorption component was present in his Hβ data, variable in both strength and velocity. For HD153919, Conti & Cowley (1975) mentioned that most absorption and emission lines show little, if any, variation with orbital phase. Like Fahlman & Walker (1980) they find that phase-dependent absorption components are present in the Hα and He i 5876 Å lines. Usually, this late-phase absorption is attributed to the presence of a gas stream in the system that partly obscures the supergiant. However, the nature of this stream is not clear and widely different suggestions about its geometry have been put forward.

To study the structure of the mass-accretion flow in HMXRBs in detail, we observed two bright optical counterparts: HD77581 (Vela X-1) and HD153919 (4U1700-37), taking advantage of the strong development in observing techniques over the last decade. In the next section we describe the reduction of the spectra we obtained. The results are described in section 3. In the last section we discuss how our results constrain on the geometry of the mass-accretion flow in these two HMXRBs.
2. Observations

Spectra of HD77581 (B0.5 Iab, $V = 6.9$) and HD153919 (O6.5 Iaf+, $V = 6.5$) were obtained with the Coudé Echelle Spectrograph (CES) attached to the Coudé Auxiliary Telescope at the European Southern Observatory in La Silla, Chile. We used the blue path and the short camera with a thinned, backside-illuminated CCD (RCA#9, 1024 x 640 pixels). Spectra were taken in the wavelength regions around He I 4471.48 Å, He II 4685.75 Å (only for HD153919), and H/β at 4861.33 Å. We monitored these lines during two shifts of three nights, from June 2nd to 5th and June 8th to 11th, 1992. In this way we covered almost two orbits of HD153919 ($P_{\text{orb}} = 3.41$ days) and part of an orbit of HD77581 ($P_{\text{orb}} = 8.91$ days).

With an exposure time of half an hour a signal-to-noise ratio of about 200 or more was obtained. Due to the high spectral resolution ($R=60000$, i.e. $\sim 5 \text{ km s}^{-1}$ per resolution element) and, consequently, the small spectral coverage of about 30 Å, we had to change the central wavelength frequently. To correct for any instrumental effects calibration frames (lamp flatfields and Th-Ar spectra) were obtained after each change of central wavelength.

The spectra were reduced using the MIDAS software package and an optimal extraction routine based on the method given by Horne (1986). The main advantage for these high-signal-to-noise

Figure 1: Normalized H/β profiles of HD77581 (Vela X-1). The spectra have been shifted vertically according to orbital phase, indicated at the left side of each spectrum. The tickmarks on the vertical scale are placed at 10% intervals. The dashed line represents the average spectrum. Note, however, that the spectra at $\phi = 0.6$ and $\phi = 0.7$ are not sequential: we started the observations at $\phi = 0.7$. 

2 Observations 

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spectra is the efficient detection and deletion of cosmic-ray events. The spectra were normalized using a second order polynomial fit to five carefully selected wavelength regions without spectral lines. The wavelength scale was converted to the system’s rest-frame velocity scale, using $\gamma = -7$ and $-64.5 \text{ km s}^{-1}$ for HD77581 and HD153919, respectively (Van Paradijs et al. 1976, Gies 1987).

3 Results

3.1 HD77581 (Vela X-1)

In Figs. 1 and 2 we show spectra of H$\beta$ and the He I line at 4471 Å for HD77581 as a function of binary phase. The displayed spectra are averages of two exposures taken within one night, except for the spectra at $\phi = 0.37$ (using the ephemeris of Deeter et al. 1987) which are single. For comparison, the average of all exposures is indicated with a dashed line. One can clearly see an extra absorption component superposed on the photospheric absorption line (assumed to be symmetric) and starting at about $-50 \text{ km s}^{-1}$ around phase $\phi = 0.5$, when the X-ray source is in the line of sight. This extra component strengthens rapidly and reaches maximum strength at $\phi \sim 0.6$; subsequently, the absorption component shifts towards higher negative velocities and gets weaker. At $\phi = 0.8$ the component is still present, extending from $\sim -175$ to $\sim -350 \text{ km s}^{-1}$ and centered at $-250 \text{ km s}^{-1}$. In the H$\beta$ line, a significant red emission component is present in the
3. Results

Figure 3: As Fig. 1; a) The He I line of HD153919 at 4471 Å: shown are averages of several spectra sometimes belonging to separate orbits. Around $\phi = 0.65$ the blue-shifted absorption gets much stronger. Note the changes in the P Cygni emission and the small absorption contribution at $\sim -650$ km s$^{-1}$ around $\phi = 0.95$; b) The strong emission line of He II at 4686 Å exhibits small but significant variations. Normalization of these spectra was quite difficult due to the extended wings of the profile. c) The H$\beta$ line is of P Cygni type and shows variations similar to those in the He I line. At $\phi \sim 0.95$ some extra emission seems present at the line center.
spectra taken at $\phi = 0.5$ and $\phi = 0.8$.

3.2 HD153919 (4U1700-37)

The spectra of HD153919, displayed in Fig. 3, clearly show the presence of orbital variations in its line profiles. The spectra shown are the averages of several individual exposures, some of them belonging to a different orbit (neglecting the orbit-to-orbit variations). The H$\beta$ line (Fig. 3a) and the He I line at 4471 Å (Fig. 3c) have P Cygni-type profiles and show a similar dependence on orbital phase. Around $\phi = 0.6$ (ephemeris of Haberl et al. 1989) the blue-shifted absorption strengthens greatly and widens, extending from $\sim 50$ to $\sim -650$ km s$^{-1}$. Around $\phi = 0.95$, when the X-ray source is almost in superior conjunction, the blue-shifted absorption is still stronger than at $\phi = 0.36$, and around $-650$ km s$^{-1}$ a small absorption component is visible, probably related to the extra absorption found at earlier phases. Also the emission component varies in strength. At $\phi \sim 0.6$ and especially at $\phi \sim 0.95$ the emission is stronger than at other phases. We note that the precise phase at which the emission reaches maximum strength depends on the orbit ($\phi_1 \sim 0.58, 0.66$ and $\phi_2 \sim 0.86, 0.97$ for the first and second rise in two different orbits). At $\phi \sim 0.95$ an extra emission component centered at zero velocity seems to be present in the H$\beta$ line.

The He II 4686 Å line is strongly in emission (Fig. 3c). Most remarkable is the left wing of the profile, which shows a strange emission "shoulder" at $\phi = 0.35$ and which is very steep and linear around $\phi = 0.6$ (possibly because of an enhancement of blue-shifted absorption). The variations in the He II line resemble somewhat the observed behaviour of this line in HDE226868/Cyg X-1 (Gies & Bolton 1986), although for HD153919 the emission line is much stronger.
4 Discussion

Many authors have suggested that the line-profile variability is due to an accretion wake or a tidal stream, similar to the interpretation of the observed X-ray absorption at late orbital phases, which is well explained by obscuration of the X-ray source by these structures (Blondin et al. 1990, 1991). However, the relative velocity of the compact object with respect to the stellar wind causes the accretion wake to be directed away from the supergiant. A tidal stream through the inner Lagrangean point will be orientated along the line of centers (Blondin et al. 1991). In fact, Carlberg (1978) showed that no appreciable obscuration of the supergiant can be achieved by means of an accretion wake, given the expected characteristic dimension of about \(10^{10}\) cm. It might be that close to \(\phi = 0.5\) the stellar disk is partly covered by the above mentioned structures, but this will probably result in only a modest absorption enhancement in the spectral lines. That the amount of extra absorption observed at phases as late as \(\phi = 0.8\) is caused by an accretion wake and/or a tidal stream seems highly unlikely.

If one adopts a monotonie “beta”-velocity law for the stellar wind (with \(\beta = 0.8\)) and a terminal velocity \(v_\infty = 1105\) km s\(^{-1}\) for HD77581 and \(v_\infty = 1820\) km s\(^{-1}\) for HD153919 (Prinja et al. 1990), one finds for the wind velocities at the location of the compact star: \(v_w = 485\) km s\(^{-1}\) and \(v_w = 1045\) km s\(^{-1}\) for HD77581 and HD153919, respectively (using the orbital parameters of Nagase (1989) for Vela X-1, and of Heap & Corcoran (1992) for 4U1700-37). These velocities are much higher than the typical velocities we find for the late-phase absorption component. Inverting the problem, one can use the observed velocities to obtain an estimate of the radius at which the absorption takes place. In Fig. 4 we have sketched the expected position of the absorbing material in the wind of HD77581 based on this method.

From Fig. 4 and the reasons given above, we propose that the observed velocity, strength, and phase-dependence of the extra blue-shifted absorption in optical spectra of HD77581 and HD153919 are in agreement with the properties of a photo-ionization wake. Specifically in the case of a low value of the ionization parameter \(q\), which determines the size of the Strömgren zone (for the definition of \(q\) see Hatchett & McCray 1977) a photo-ionization wake is expected. For HD77581, independent evidence for an extended Strömgren zone (\(q \sim 2\)) in the wind comes from the observed orbital modulation of UV resonance lines (Dupree et al. 1980). Recently, Kaper et al. (1993) reanalyzed the UV spectra of HD77581 and discovered that ionization effects also occur at very low wind velocities (up to \(v_w \sim -250\) km s\(^{-1}\)), implying an even lower value of \(q\). For such low values of \(q\) the numerical calculations of Blondin et al. (1990) show that the column density of the photo-ionization wake, which is located at the trailing border of the Strömgren zone, can become very large. For very small values of \(q\) the photo-ionization wake wraps around the supergiant, and can increase the observed column density even at late phases, possibly all the way into eclipse.

Although a low value for \(q\) is expected for HD153919 (4U1700-37) as well (Hatchett & McCray 1977), no orbital modulation is observed in the UV resonance lines of this system. This may indicate that velocity and density of the stellar wind depend non-monotonically on radius (Kaper et al. 1993). In this way the Strömgren zone, which is certainly present in the wind of HD153919, could be hidden from detection in the UV resonance lines, because sufficient scattering ions are left outside the Strömgren zone to keep these profiles saturated.

As a final note, the ionization parameter \(q\) is proportional to the X-ray luminosity. For these systems, the observed X-ray luminosity is highly variable (Watson & Griffiths 1977, Haberl et al. 1989). Large flares, with sometimes a factor of 100 increase in X-ray luminosity, do occur on a time scale of a day. This will cause variations in \(q\) and therefore a changing size of the Strömgren zone. The precise phase and velocity dependence of the late-phase absorption will thus be a function of the X-ray luminosity, which could explain the observed orbit-to-orbit variations.

Modelling of the late-phase absorption in optical spectra, using the 2-D hydrodynamical simulations of Blondin and coworkers, is presently underway. The results will be presented in a following
paper. Also simultaneous optical, UV, and X-ray observations of HD77581 are currently planned and will hopefully help us to construct a detailed model of the material flow within the system.

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