A Massive Star Odyssey, from Main Sequence to Supernova
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FUSE observations of the SMC Wolf-Rayet binary Sand 1 (WO4+O4V): atmospheric eclipses and colliding winds

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Abstract. We present *FUSE* observations of the SMC WO4+O4V binary Sand 1. Our spectra show variations in S IV, C III, C IV and O VI lines, which we attribute mainly to emission from the shock cone, resulting from the collision between the two winds, and to atmospheric eclipses of the O-star continuum light by the WR wind. From this variability, we deduce a cone opening angle of 120°.

1. When two mighty winds meet

When the winds of two hot, massive stars in a binary interact, two main phenomena occur: (*i*) a shock-cone forms where the momentum fluxes of the winds are equal. As the heated gas flows along the shock, it cools and emits light in lines of gradually decreasing ionisation potential; (*ii*) the WR wind absorbs the O-star light in certain lines. This is the so-called *atmospheric eclipse*. The shape of the absorption is determined by the wind density and velocity encountered by the light. Comparing the spectral variability generated by these phenomena with models, allows one to constrain various wind and orbital parameters.

2. The observations

We have secured 18 *FUSE* spectra of the WO4+O4V binary Sand 1 and retrieved 4 archival spectra. The lines that dominate the spectrum are formed in the WR wind: S IVλ933/945, C IIIλ977, O VIλ1032/1038 and C IV + C IIIλ1168 + λ1175. This binary has a circular orbit with a period of 16.64 d and an orbital inclination of 68° (obtained from polarisation data of one of us, AFJM).

3. Some results

Close inspection of the spectra reveals similar variations in the S IV, C IIIλ977 and O VI lines. Excess emission from the shock cone is clearly seen in the O VI greyscale plot presented in Figure 1 as a bright feature, moving from the red to

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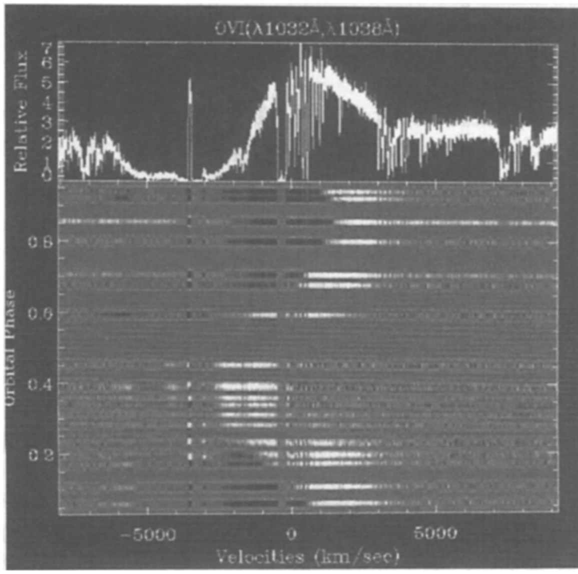

Figure 1. Greyscale plot for O VIλ1032/1038 of the differences between individual spectra and the reference spectrum plotted at the top.

the blue from phase 0 (WR in front) to 0.5, and back again from 0.5 to 0. The figure presents differences between individual spectra and the reference spectrum plotted above, as a function of orbital phase (orbit from Moffat *et al.* 1990).

Atmospheric eclipses are clearly visible in Figure 1 as a dark feature with a decreasing width from phase 0 to 0.5, as expected from the system geometry. The C IV + C III line also shows this behaviour, but an additional emission moving in anti-phase with the excess shock emission is present with a central velocity of $-2700\,\mathrm{km\,s^{-1}}$ if due to C III, or $-1000\,\mathrm{km\,s^{-1}}$ if from C IV and an amplitude of $1000\,\mathrm{km\,s^{-1}}$. We have yet to identify the precise origin of this feature.

From the equations derived by Lührs (1997):

$\mathrm{FWHM_{ex}} = C_1 + 2v_{\mathrm{str}}\sin\theta\sqrt{1-\sin^2 i\cos^2\phi}$, and $\mathrm{RV_{ex}} = C_2 + v_{\mathrm{str}}\cos\theta\sin i\cos\phi$, which describe the displacement ($\mathrm{RV_{ex}}$, these data) and width variations ($\mathrm{FWHM_{ex}}$, from the eclipse-free C IVλ5808 line in Bartzakos *et al.* 2001) of the excess shock emission, we estimate that the shock opening angle $\theta = 120°$. This agrees very well with the value of 122° calculated with the equation of Usov (1992) ($\theta(°) = 120(1 - \eta^{\frac{2}{5}}/4)\,\eta^{\frac{1}{3}}$), where η is the momentum ratio of the two winds.

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