Outline

I. A taste of the interesting hydrodynamics

II. Particle acceleration in CWBs

III. Conclusions and further work
CWBs are hugely diverse

<table>
<thead>
<tr>
<th>System</th>
<th>Orbital Period (d)</th>
<th>Separation (AU)</th>
<th>Density (cm$^{-3}$)</th>
<th>$\chi_{WR}$</th>
<th>$\chi_{O}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR 139 (V444 Cyg)</td>
<td>4.2</td>
<td>0.2</td>
<td>$\sim 10^{10}$</td>
<td>$&lt;&lt;1$</td>
<td>$?$</td>
</tr>
<tr>
<td>WR 11 (γ$^{2}$ Vel)</td>
<td>78.5</td>
<td>0.81-1.59</td>
<td>$\sim 10^{9}$</td>
<td>$\sim0.5-1$</td>
<td>$\sim250-500$</td>
</tr>
<tr>
<td>WR 140</td>
<td>2899</td>
<td>$\sim1.7-27.0$</td>
<td>$\sim10^{9}-10^{7}$</td>
<td>$2-50$</td>
<td>$\sim150-2000$</td>
</tr>
<tr>
<td>Eta Car</td>
<td>2024</td>
<td>$\sim1.5-30$</td>
<td>$\sim10^{12}$</td>
<td>$&lt;&lt;1$</td>
<td>$\sim1-50$</td>
</tr>
<tr>
<td>WR 147</td>
<td>$&gt;10^5$</td>
<td>$&gt;410$</td>
<td>$\leq 10^{4}$</td>
<td>$&gt;30$</td>
<td>$&gt;1000$</td>
</tr>
</tbody>
</table>

Winds may achieve ram-pressure balance, or the stronger wind may overpower the weaker (for all or part of the orbit)

2 different regimes determined by characteristic cooling parameter, 

$$\chi = \frac{t_{cool}}{t_{dyn}} \approx \frac{v_8 D_{12}}{\dot{M}_{-7}}$$

i) $\chi << 1$ - shocked wind highly radiative, wind-collision region (WCR) subject to thin shell instabilities

ii) $\chi >> 1$ - cooling mostly due to adiabatic expansion, WCR stable (except KH instability)
Dynamical Instabilities

\[ \chi_{1,2} \gg 1 \quad \chi_1 \gg 1, \chi_2 < 1 \quad \chi_{1,2} < 1 \]

Stevens et al. (1992)

Lamberts et al. (2012)
Spiral structure

2D calculations
Lamberts+ (2012)
3D simulations with radiative driving

Cold plasma inside WCR

Wind speeds faster where radiative flux reinforced, relatively slower in shadows behind stars

Leading side of WCR arms less susceptible to instabilities

O6V + O6V, P=3d, Dsep = 35 Rsun

χ << 1

Pittard (2009)
Eccentricity – introduces “time lag” effects

O6V + O6V, P=6.1d, dsep = 35-75 Rsun, e=0.36

Pittard (2009)
X-ray Hysteresis in Eccentric Systems

- Hysteresis now seen for the first time! Cyg OB2#8A (Cazorla+2014)
- Phase-behaviour is a little different to current theoretical models (of a generic system)
- Need dedicated model of this system
Post-shock plasma is expected to have $T_e < T_i$. Best fit to X-ray data indicates $T_e/T_i = 0.1$.

Parkin et al. (2014)
WN7 + O9V
P = 80.3d
e = 0.56
a = 1.68 AU

Parkin & Gosset (2011)
Eta Car

Parkin et al. (2011)

LBV + ? (WR/O)
P = 2024 d
e ~ 0.9
a ≈ 15.0 AU

Parkin et al. (2011)
Interaction of clumpy winds?

Clump destruction in adiabatic CWBs (Pittard 2007)

How about in radiative CWBs?

Also implications for particle accn?
Reconnection?
Stochastic accn?
Radiative coupling effects

Radiative inhibition (Stevens & Pollock 1994)
- Pre-shock velocities decrease
- $\dot{M}$ may decrease or increase

Radiative braking (Owocki & Gayley 1997)
- More powerful than inhibition
- Highly non-linear to effective opacity of wind

Self-regulated shocks Parkin & Sim (2013)
- Enhanced ionization of winds by the WCR reduces radiative driving – can greatly increase the range of separations where wind-star collisions occur (also may make radiative braking less effective)
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First Direct Proof of Colliding Winds Model

WR147: WR+OB binary
High resolution observations
- MERLIN @ 5GHz:
  50 mas = 77AU @ 650pc

Two components, S is thermal, N is non-thermal

NT emission => relativistic electrons + magnetic fields
NT emission consistent with wind-collision position

Williams et al. (1997)
WR 146 - brightest radio CWB

VLA 43-GHz shows the southern thermal source that is associated with the WR star and the northern non-thermal emission from the WCR.

VLBA 8.6-Ghz reveals the structure of the WCR.

Crosses mark the relative location of the two stars.

Courtesy Sean Dougherty
WR140 – the particle acceleration laboratory

WR + O in a 7.9 year, eccentric (e ~ 0.9) orbit

Orbit size ~ 1.5-28 AU

Radio-bright; dramatic variations in radio emission as orbit progresses

State of the Art imaging!
23 epochs @ 3.6 cm
Phase ~ 0.74 -> 0.93
(Jan 1999 to Nov 2000)
Resolution ~ 2 mas
Linear res ~ 4 AU

Dougherty et al. (2005)
The radio light curve of WR140

8 years of VLA (White & Becker 1995) + WSRT (Williams et al 1991) data
Visibility of NT emission vs. binary period

Dougherty & Williams (2000)
Models

Early models of NT emission were simple

Radio:

- **Point source** non-thermal emission, spherically symmetric winds –

\[
S_{\text{obs}}^{\nu} = S_{\text{thermal}}^{\nu} + S_{\text{nt}}^{\nu} e^{-\tau_{\nu}^{R}}
\]

- maintains analytic solutions

A more complex model would account for the hole in the WR wind carved out by the O wind

![Modelled emergent flux](image)
Previous models

Early models of NT emission were simple

Radio:

- **Point source** non-thermal emission, spherically symmetric winds –
  \[ S_{\nu}^{\text{obs}} = S_{\nu}^{\text{thermal}} + S_{\nu}^{\text{nt}} e^{-\tau_{\nu}} \]
  - maintains analytic solutions

A more complex model would account for the **hole in the WR wind** carved out by the O wind

White & Becker (1995) pointed out that even the O wind has significant opacity

No consideration cooling mechanisms (e.g. IC cooling – important even for wide systems) or other absorption (e.g. Razin effect)
A phenomenological model

1.6 GHz emission map

Pittard et al. (2006)
Example synthetic emission maps

No IC cooling

With IC cooling

1.6 GHz

22 GHz
Spectral fits to WR140 spectra

Model A: \( \eta = 0.22, p = 1.4, \zeta_e = 1.4 \times 10^{-3}, \zeta_B = 0.05 \)

Model B: \( \eta = 0.02, p = 1.4, \zeta_e = 5.4 \times 10^{-3}, \zeta_B = 0.05 \)

A caveat – \( p \) and \( \zeta_B \) are ill-constrained parameters in these models

Crucially, we cannot obtain fits with \( p = 2 \)!
Modelling 8 GHz VLBA observations

Possible to constrain models with VLBI obs – demands “good” observations
Gamma-ray absorption

Two-photon pair production: $\gamma + \gamma^* \rightarrow e^- + e^+$

Pair production in electric field of charged nuclei is negligible.
High energy emission at phase 0.837

\[ \Gamma = -0.7 \text{ at } 1 \text{ keV} \]
\[ \Gamma = 1.65 \text{ at } 1 \text{ MeV} \]
\[ \Gamma = 3.7 \text{ at } 20 \text{ GeV} \]

- Radio
- ASCA
- Inverse Compton
- NT bremsstrahlung
- Pion decay
Fits at phase 0.41 and 0.907 and lightcurves
Colliding wind binaries are incredibly diverse, and are important laboratories for investigating shock physics and particle acceleration.

Highly eccentric systems – like WR140 – are particularly useful.

Our understanding of the wind dynamics has come a long way in recent years.

There are still some puzzles to work out, e.g.:

1. X-ray emission from close binaries (2 component wind vs. NTSLI suppression of X-rays vs. something else?)
2. Particle Acceleration (2\textsuperscript{nd} order Fermi vs. reconnection, efficiency, what really controls whether we see NT emission or not?)
3. Dust formation (not discussed in this talk…)

One hopes that these puzzles will be gradually worked out…