UNIVERSITY OF BIRMINGHAM | COLLEGE OF ENGINEERING AND PHYSICAL SCIENCES

RADIO EMISSION FROM MASSIVE STARS

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Summary

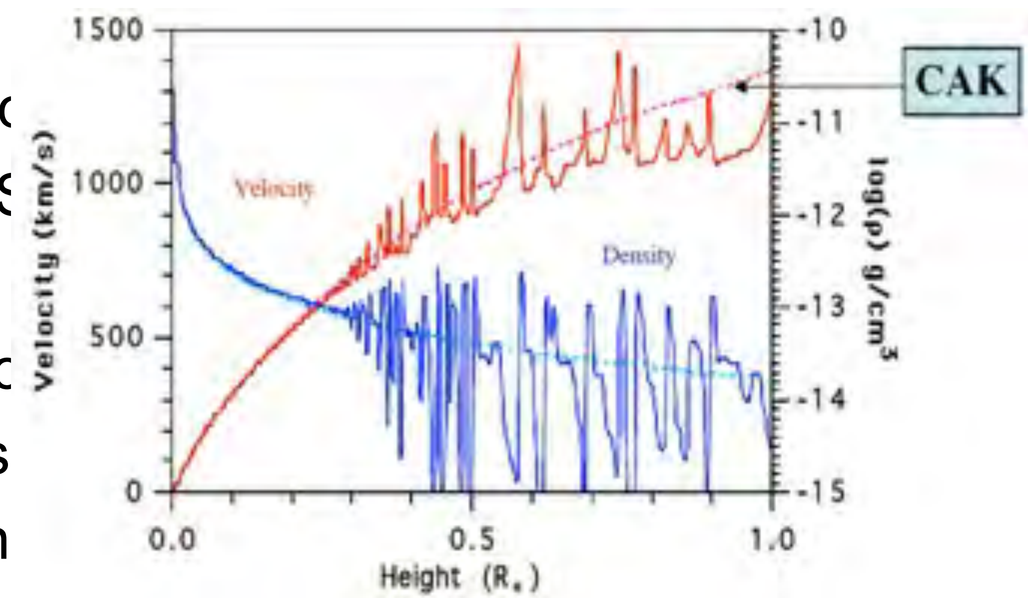
- Basic Winds Physics
- Radio Emission Processes – thermal and non-thermal
- Case study: Single stars
- Case study: Colliding wind binary systems
- Magnetic Chemically Peculiar Stars
- Line Emission (RRLs)
- Future Prospects

Basic Wind Physics

Massive stars have strong winds.

The winds are radiatively driven - line absorption – described by Castor, Abbott & Klein (CAK) theory.

These winds are crucial tc
and their impact on the IS



Much remains unclear – c
unstable – still controvers
the degree of clumping, h

Radiative driving even more complex in massive binary systems binary – opposed radiation fields, sudden radiative breaking etc.

Type of Stars

- Wolf-Rayet Stars: Very strong and fast winds – defined by their unusual abundances – WN/WC/WO subtypes.

- O and early B-type stars: typically fast winds, but with a wide range of mass-loss rates (from O4 supergiants down mid-B main sequence stars. Some have measurable B-fields.

- Luminous Blue Variable (LBVs): massive and slow winds.

- Magnetic Chemically Peculiar (MCP) stars: late B/early A-types. Very weak winds, but some have strong B-fields.

Radio Emission Processes

- Free-free (thermal) the winds are ionised and so will emit free-free emission – observed emission is a combination of optically thick and thin – spectral index of α=+0.6.

A ρ^2 process – affected by clumping.

- Shock acceleration – synchrotron emission from electrons, Fermi accelerated by the wind-wind collision shock in colliding wind binaries (single stars?). Spectral index α<0.0.
- Reconnection – for systems with B-fields, reconnection events can also provide particle acceleration.
- Electron Cyclotron Maser (ECM) emission – under some conditions an ECM can occur – MCP stars (as well as brown dwarfs and planets).

Radio Absorption Processes

- Free-free absorption – gives rise to characteristic thermal spectrum and also can absorb synchrotron emission in colliding wind systems at low frequencies.

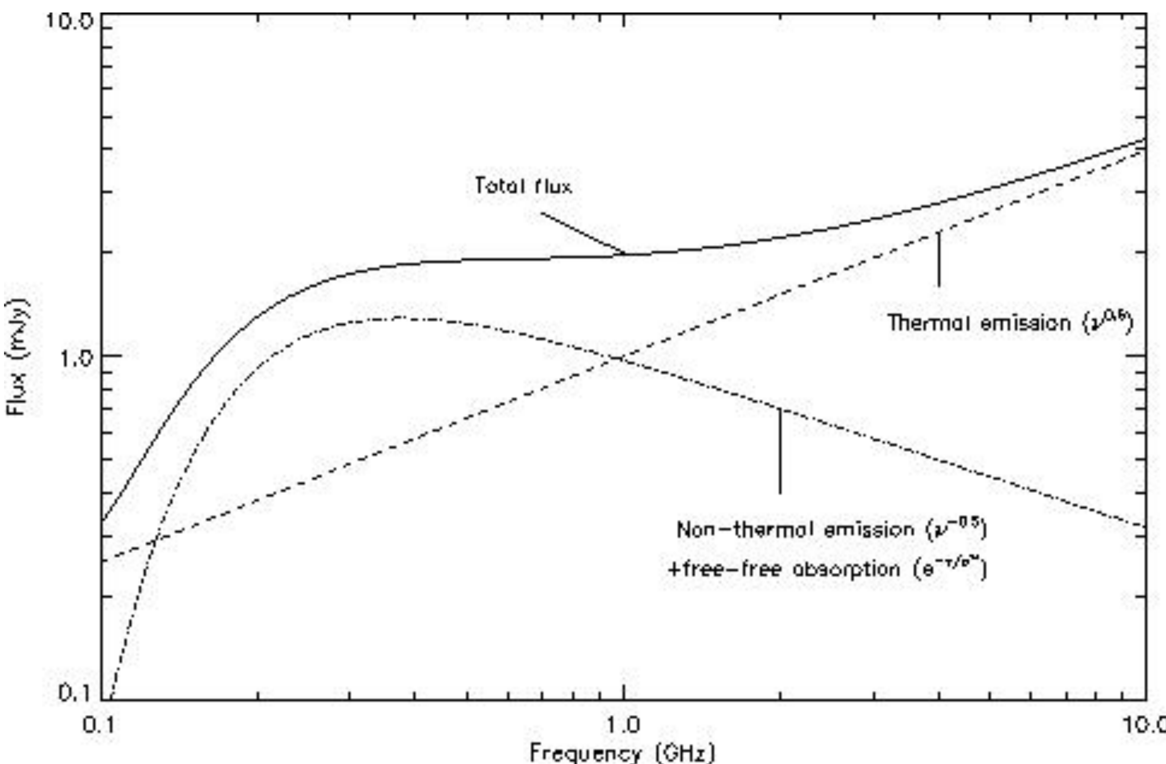
- Razin effect – for relativistic particles in a medium, beaming effect is suppressed and provides (in effect) low frequency absorption.

- Synchrotron Self-Absorption (SSA).

All 3 effects gives rise to low frequency absorption and difficult to disentangle. (Especially given lack of good data).

Radio Spectrum – schematic

Schematic of the emission from a binary system with thermal and non-thermal emission plus low frequency free-free absorption.



Thermal Radio Emission

The radio flux as a function of frequency ν for a star with mass-loss rate Mdot and wind terminal velocity Vwind, scales as (Wright & Barlow 1975 and Panagia & Felli 1975):

The Gaunt factor results in a spectral slope of +0.6.

The characteristic radius scales as:

The radio flux increases with increasing frequency, while the characteristic radius decreases. The characteristic radius is very large at low frequency, much less so at high frequencies.

At some point the wind acceleration regime comes into view – changes to spectral shape.

Thermal Radio Emission: wind acceleration region

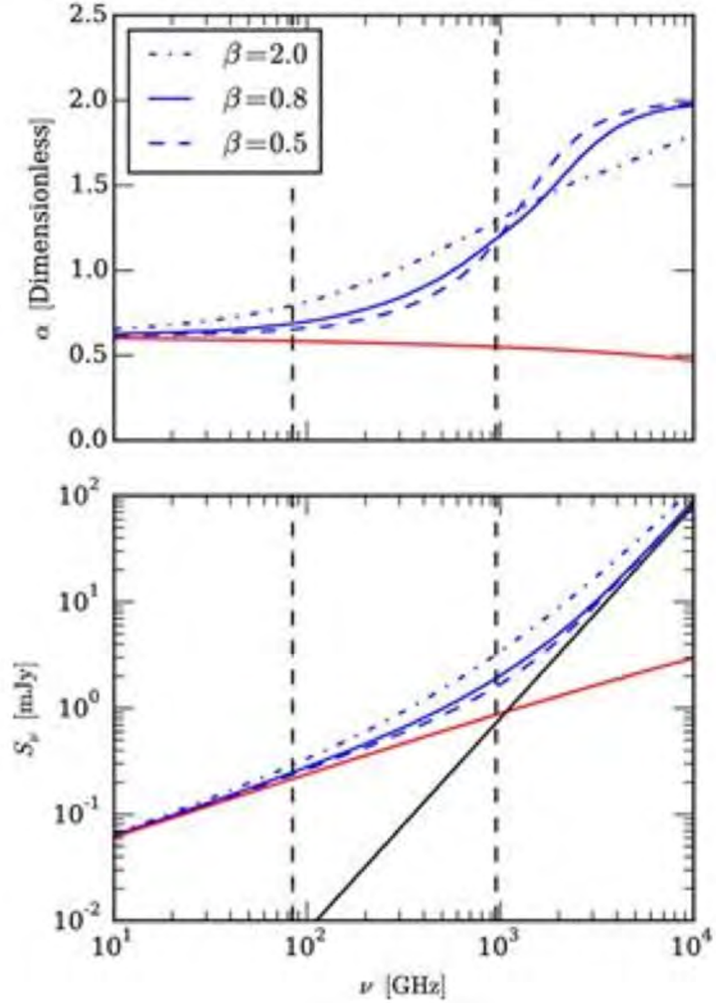
For a star with Mdot=10^{-6} Msun/yr and Vwind=2000km/s.

R_{char} (1GHz)=1800Rsun

R_{char}(600GHz)=20 Rsun

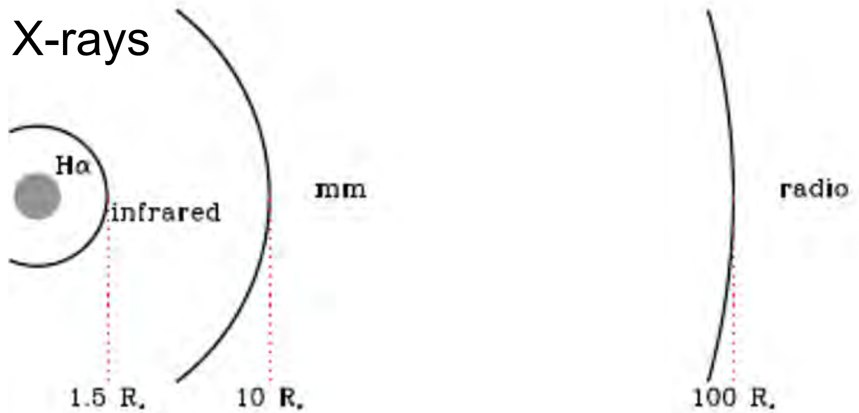
The WB75 results assumes a terminal velocity wind – can calculate effect of wind acceleration – increases spectral index and depends on wind velocity beta.

Clumping also affects emission – if clumping is radius dependent (likely), it will also effect spectral shape.



Daley-Yates et al. 2016

Stratification in Stellar Winds: Different frequencies

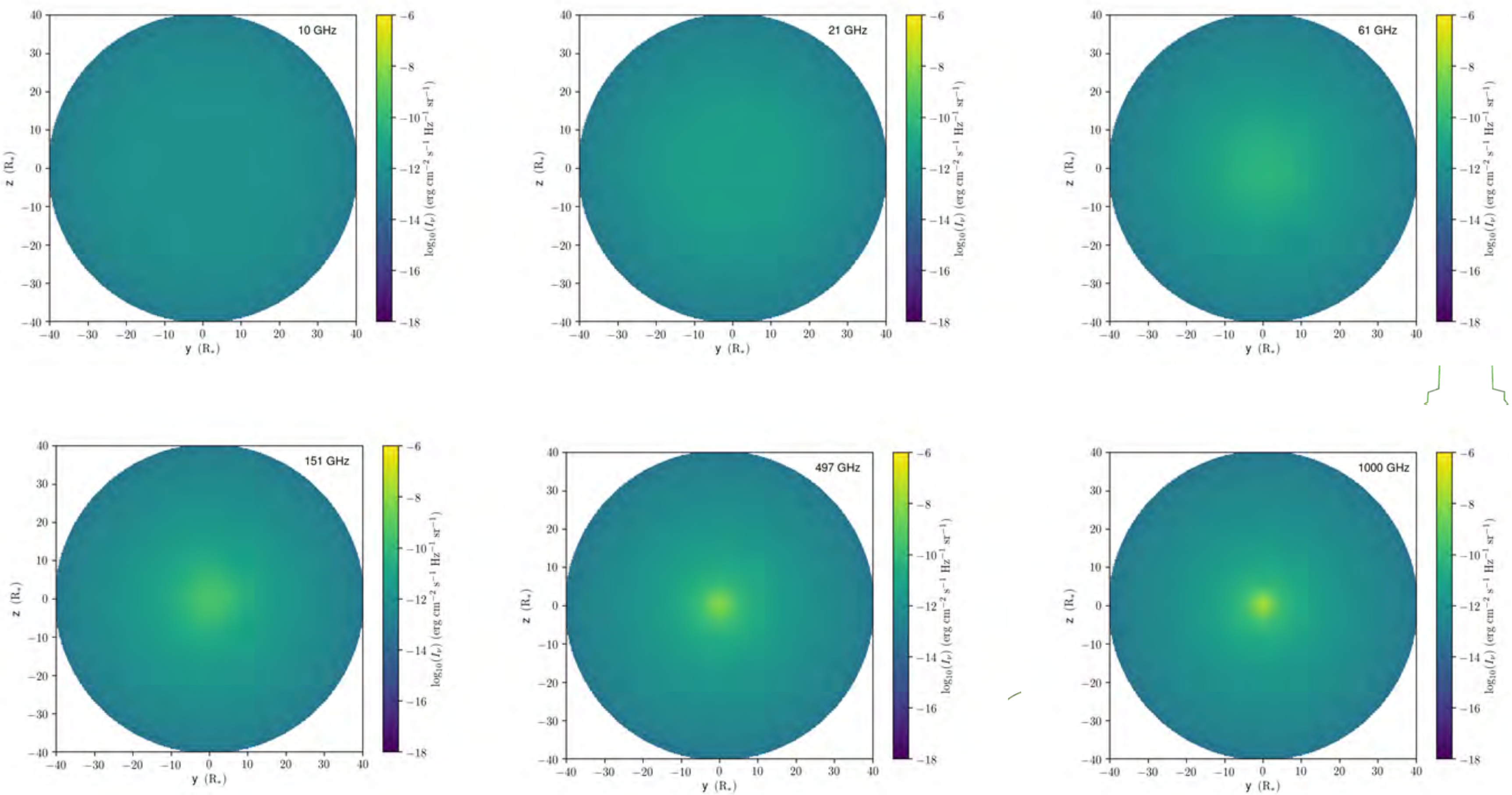


Hα/UV/X-rays come from inner region – we see corotating interaction regions (CIRs) and X-ray variability. If star has a B-field, the magnetosphere likely to be with several R_* .

Blomme 2011

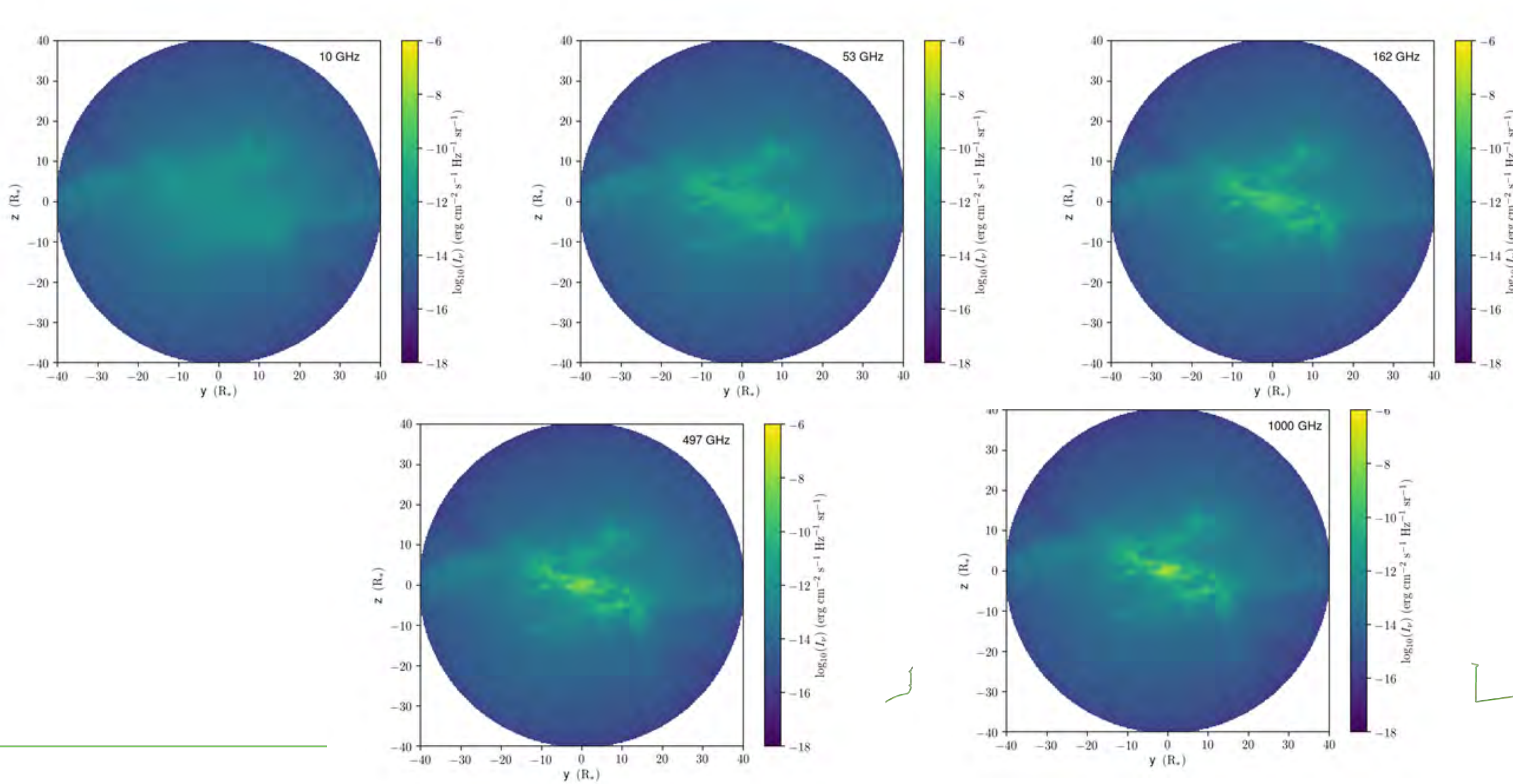
Stratification in Stellar Winds

Example of expected radio emission as a function of frequency for an assumed spherically symmetric (but accelerating) wind – emission becomes more centrally peaked at higher frequencies.



Stratification in Stellar Winds

If we do proper AMR MHD hydro simulations – of a misaligned magnetic rotator – complex magnetospheric structures more prominent at high frequencies.



Case Study for a Single Star: Zeta Puppis

Very bright and nearby massive O4 supergiant – often seen as prototypical massive O-star.

Now known to be a rapid rotator – period 1.78 days and we see a connection between surface “spots” and optical wind lines.

Star parameters

M~ 56 Msun

R~19Rsun

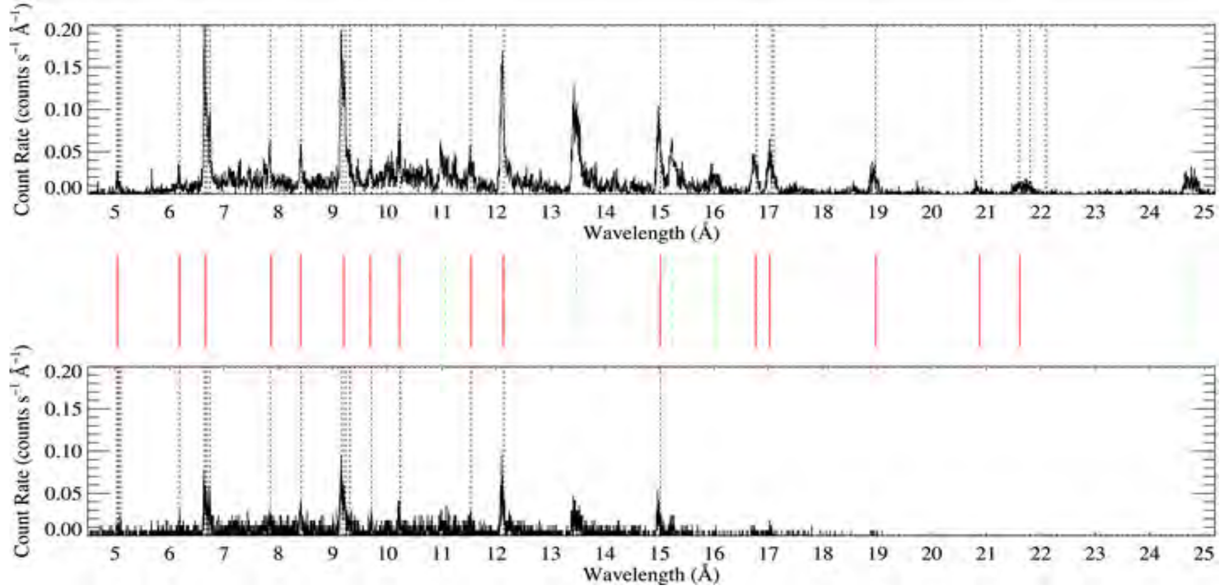
T~40kK

Mdot~2e-6Msun/yr

L~8e5Lsun

Zeta Puppis: X-ray emission

Chandra data – rich and complex line emission spectra (Cohen et al.)

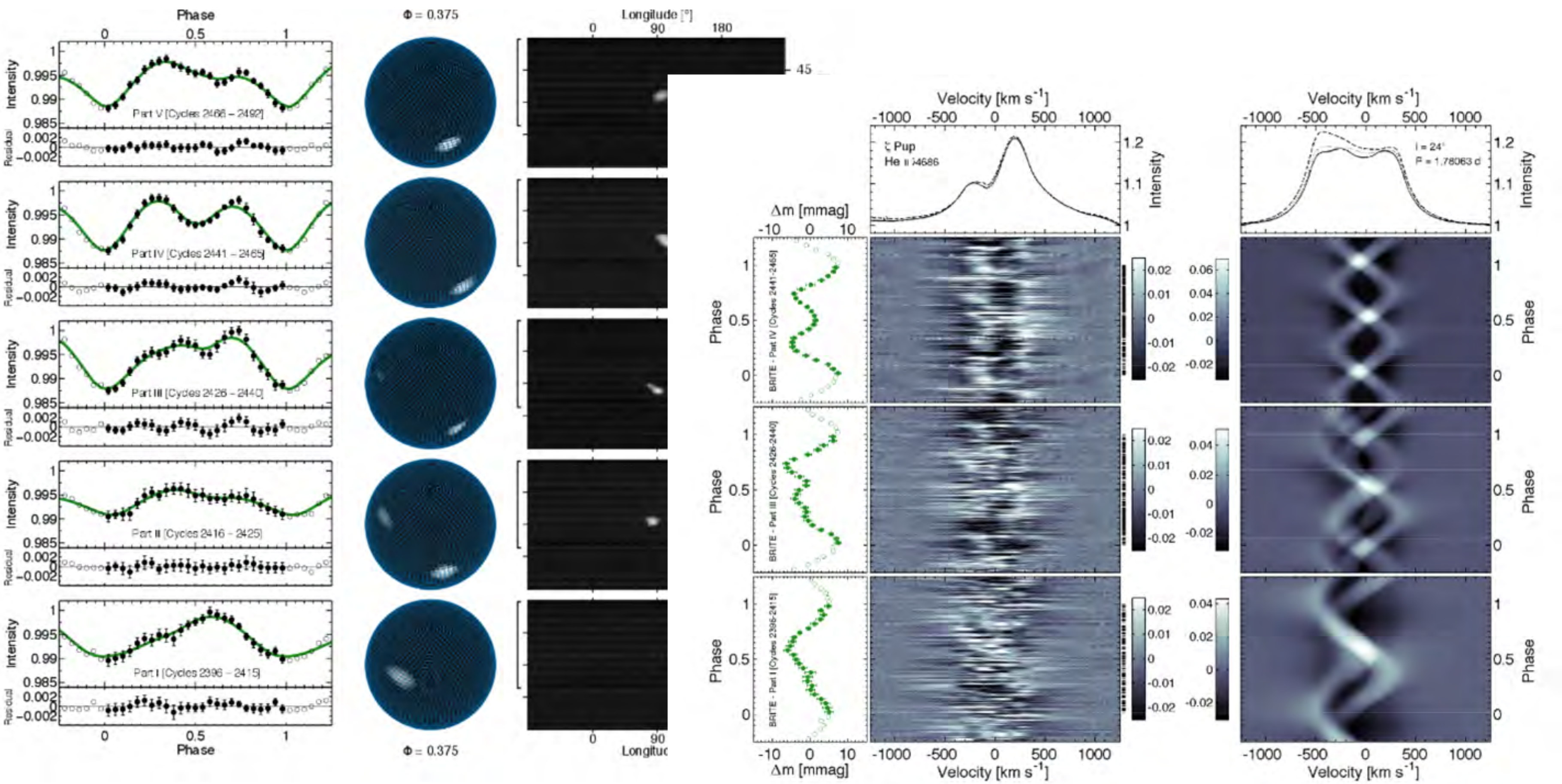


Broad and asymmetric line profiles (fir triplets)
XMM RGS data (Herve et al.).

Variable at around 10% level on timescales of a few hours – stochastic, but with break in power spectrum.
X-ray emission from the wind – shocks within the wind.

Case Study: Zeta Puppis

Optically: photometric variability due to long lived bright surface spots and rotation period of 1.78 days. Also see optical wind lines with same period – CIRs.

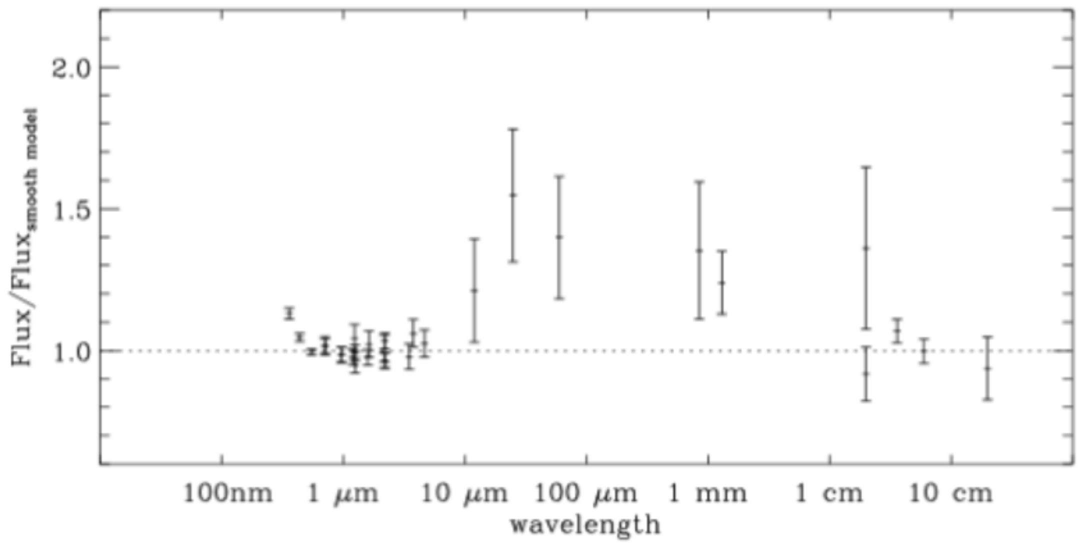


Ramiaramanantsoa et al. 2017

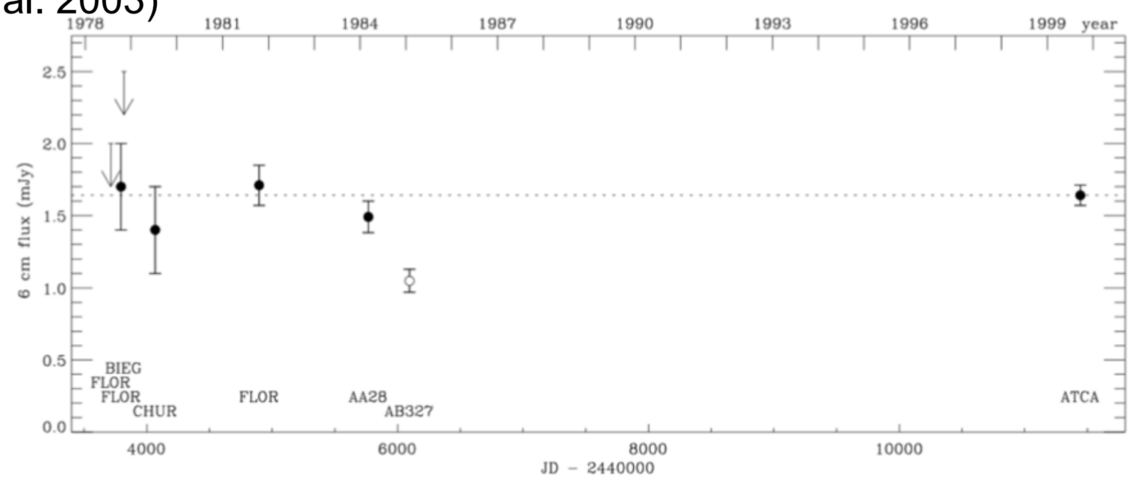
Case Study: Zeta Puppis: Radio

Variability – very limited sampling and corresponding poor constraints on variability

Spectral coverage – evidence of excess emission (over a smooth model). Probably evidence of clumping, but still poorly constrained (or ionization changes or wind acceleration)



(Blomme et al. 2003)

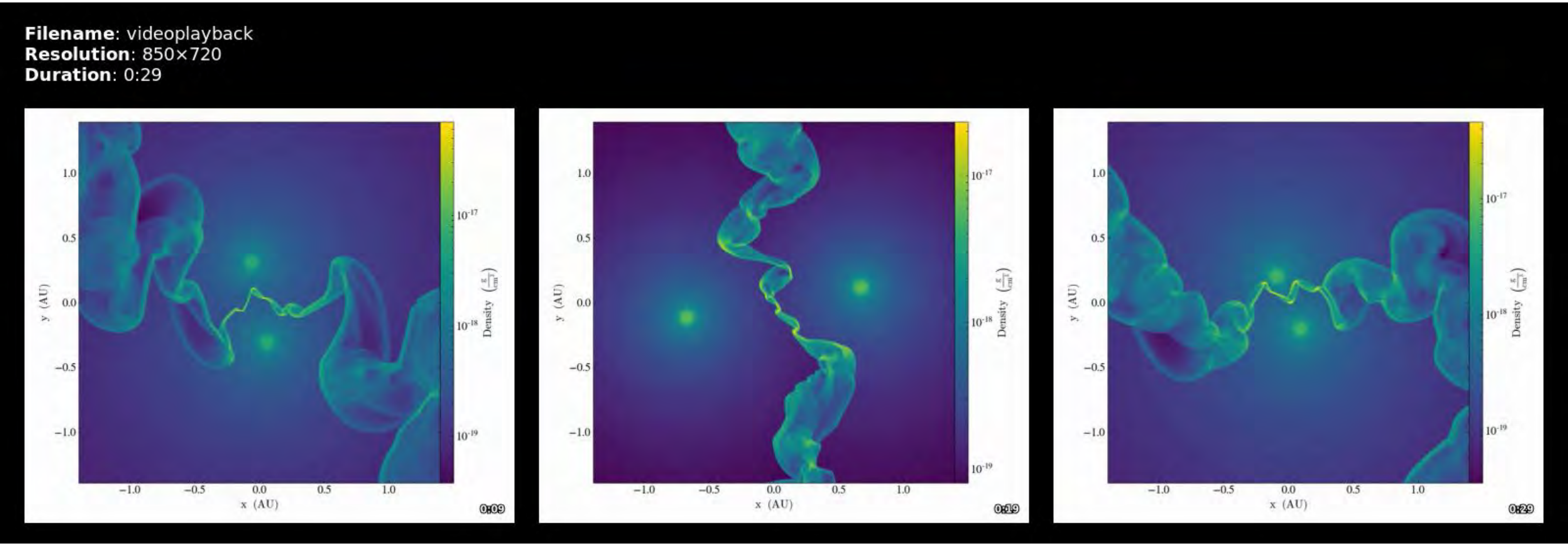


Colliding Stellar Winds

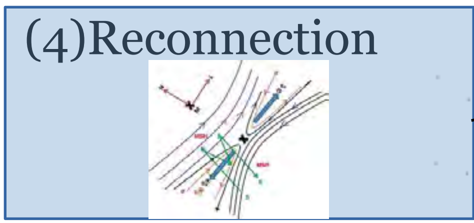
Most massive stars are in binary systems, with periods ranging from ~day to 1000's of years, many with large eccentricities.

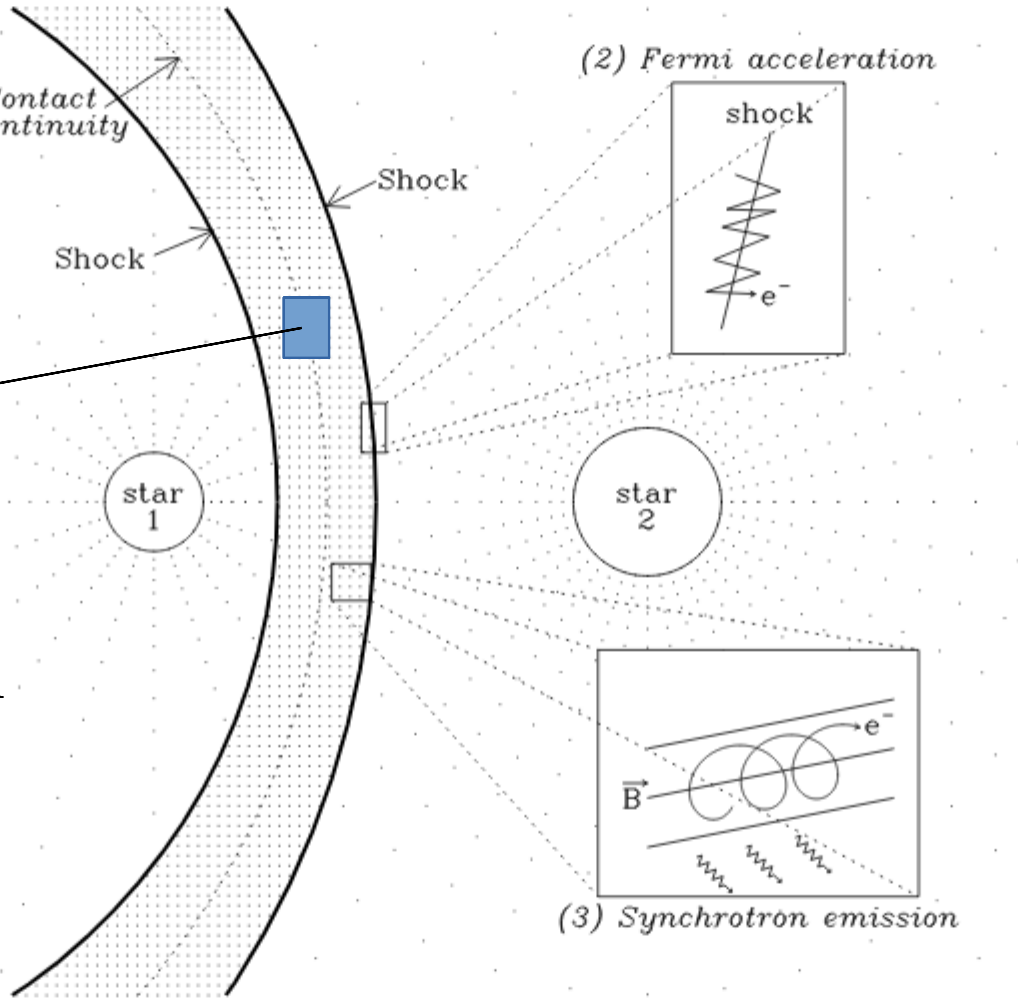
Complex hydrodynamic problem – structure of wind-wind collision (WWC) determined by ratio of wind momenta and degree of cooling.

WWC shocks likely site of particle acceleration.



Colliding Winds: Schematic



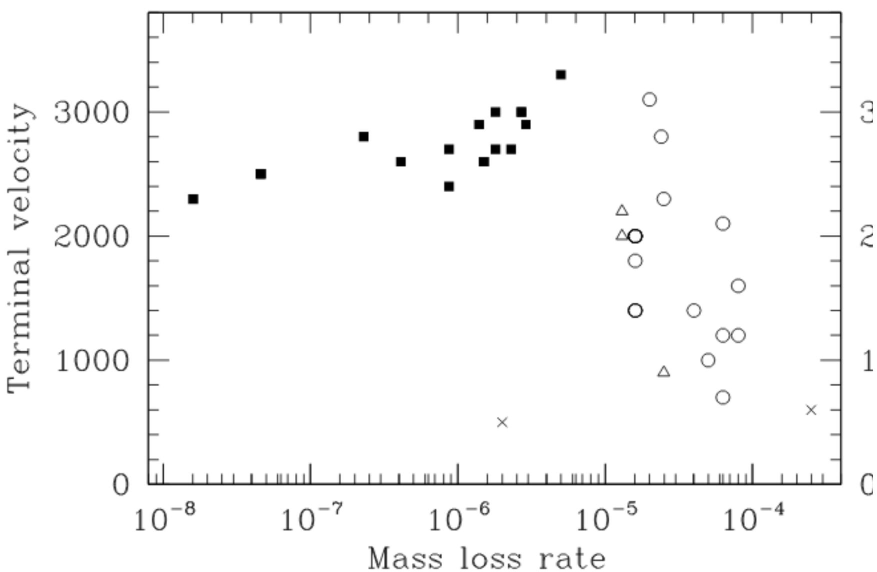


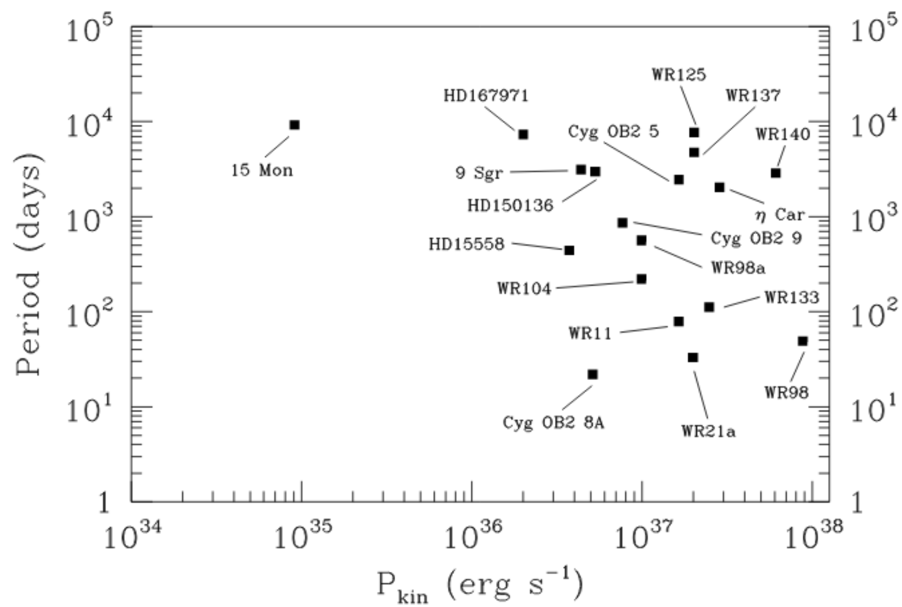
Also free-free absorption will depend on system orientation.

Blomme et al. 2011

Non-Thermal Radio Emitters

Non-thermal (NT) radio emission seems to be related to binarity, but in a complex way – some systems show NT emission, other do not.





No clear correlations

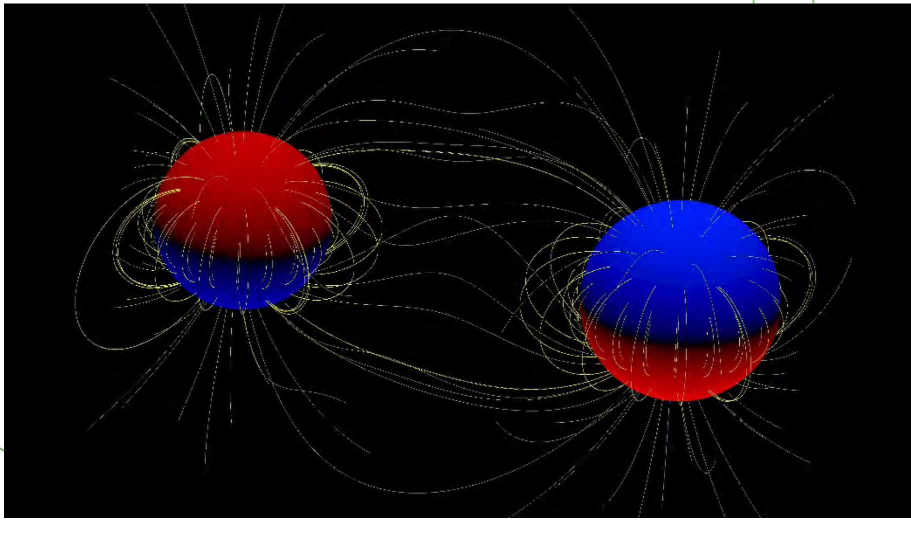
De Becker & Raucq catalogue of PACWB (Particle Accelerating Colliding Wind Binaries).

Reconnection in Massive Binary systems

A small fraction of massive stars in binaries have observed B-fields – example is Epsilon Lupi (P=4.6 days, early B-type stars). Fields are misaligned.

The amount of reconnection (and particle acceleration and non-thermal emission will depend sensitively on B-field alignment.

Instabilities in colliding winds will confuse the picture, by mixing up the B-fields.

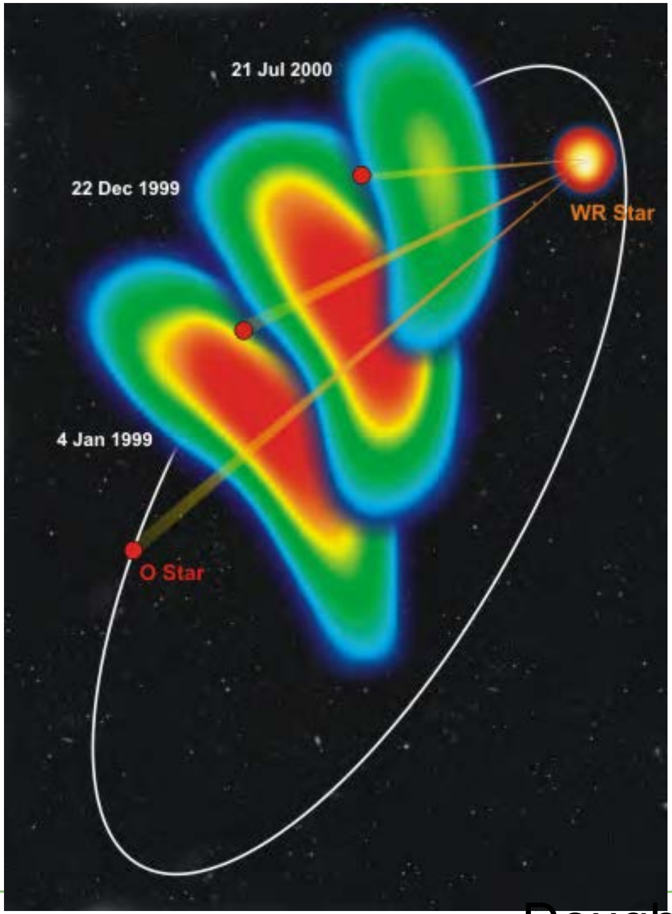


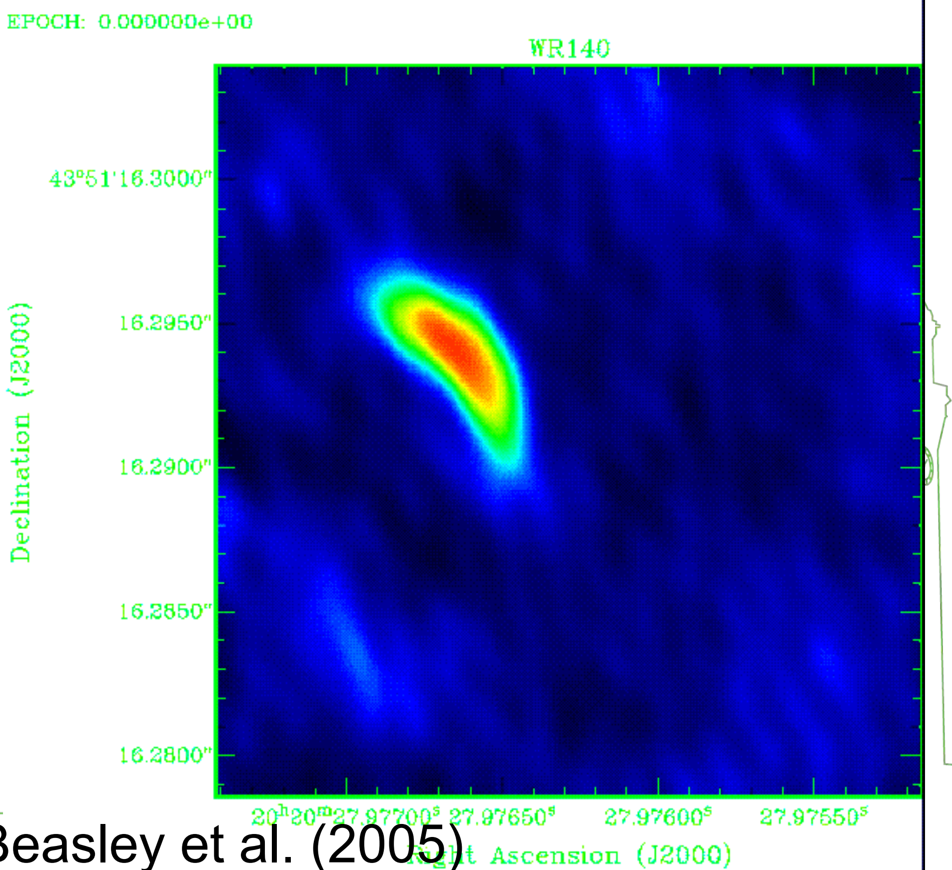
Schulz et al 2015 (Binamics)

Case Study: Colliding Winds: WR140

VLBA observations of WR140.

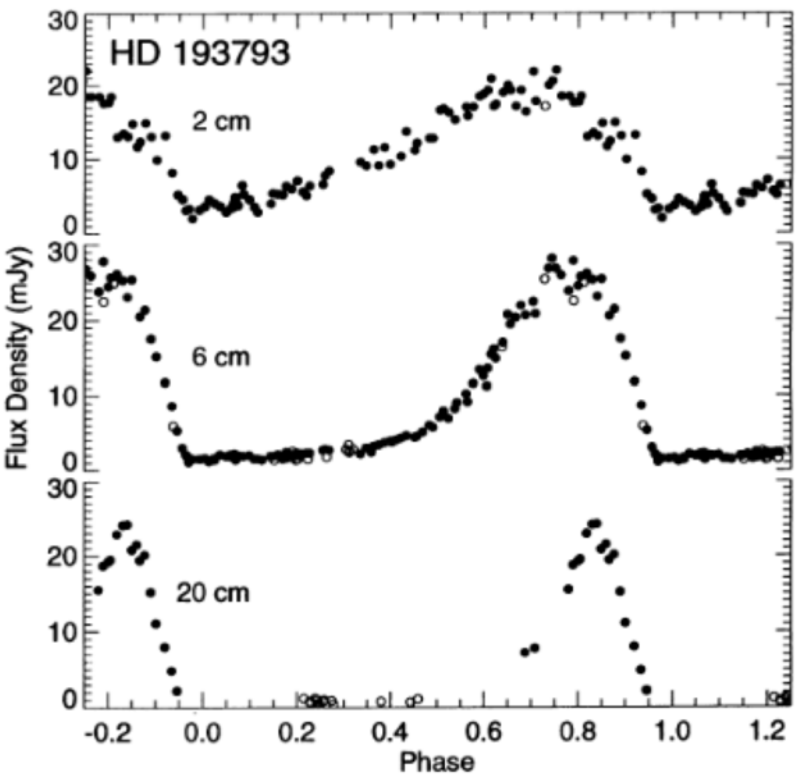
WC7+O5 binary. P~7.9 years, e=0.9.

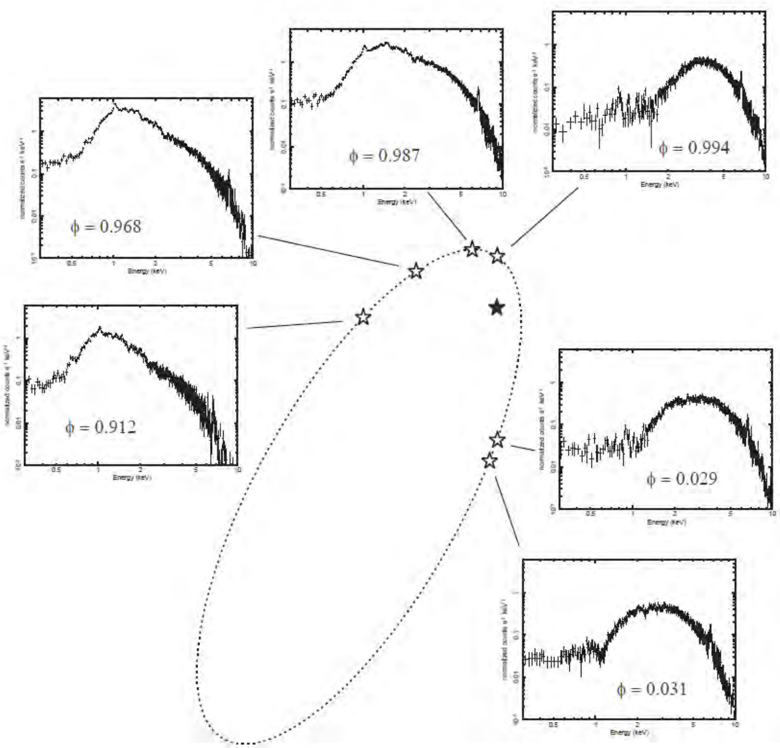




Dougherty, Beasley et al. (2005)

WR140: Radio and X-ray





Complex radio and X-ray changes – especially around periastron – both changes in emission and level of absorption.

HD93129A

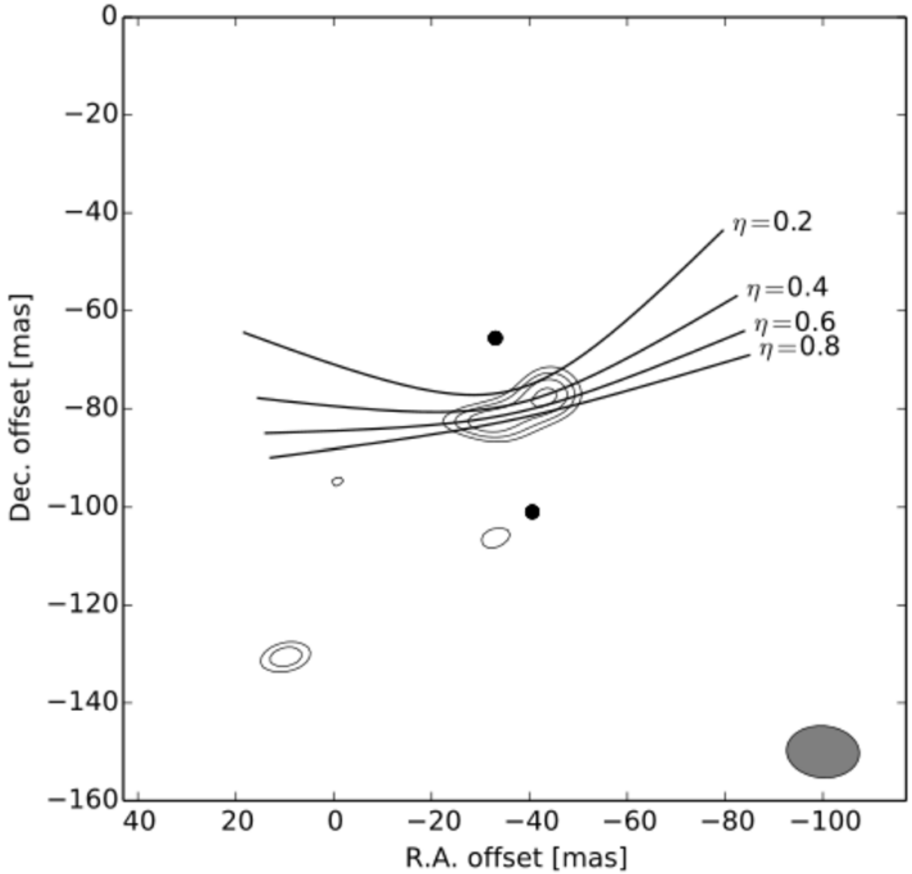
Massive binary in Carina

O2If+O3.5V

System mass ~200Msun

LBA observations at 1.3GHz

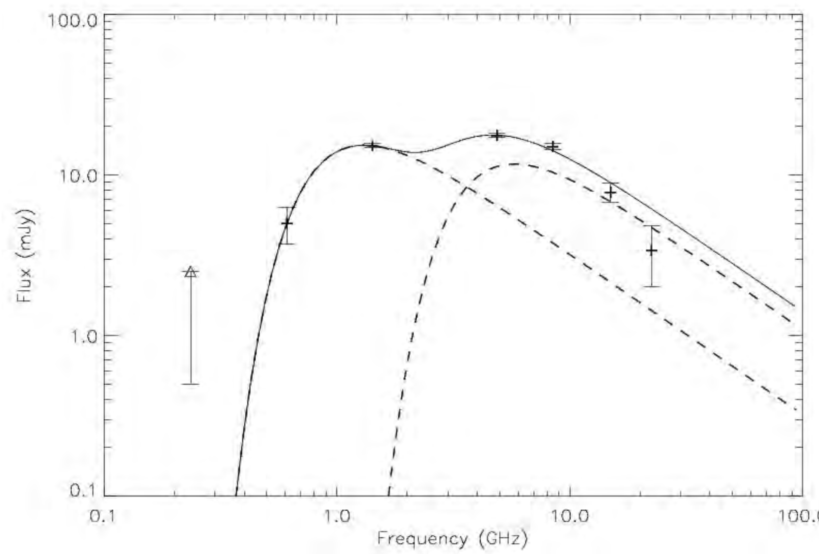
NT emission quite localised at apex of wind-wind collision.



Benaglia et al. 2015

Low-Frequency Radio Emission from Colliding Wind Binaries

WR147 – can use GMRT observations to constrain low frequency turnover in NT emission (235+610MHz). Not fit by simple model.



WR147 – e-Merlin observations

WN8_B0.5V system, with P>1000 years.

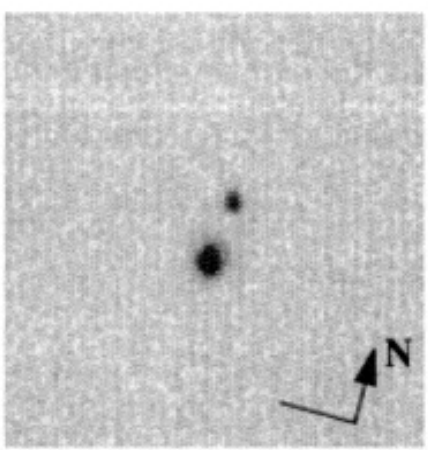
Stars resolved in HST FGS

E-Merlin shows complex emission associated with WR star and wind collision

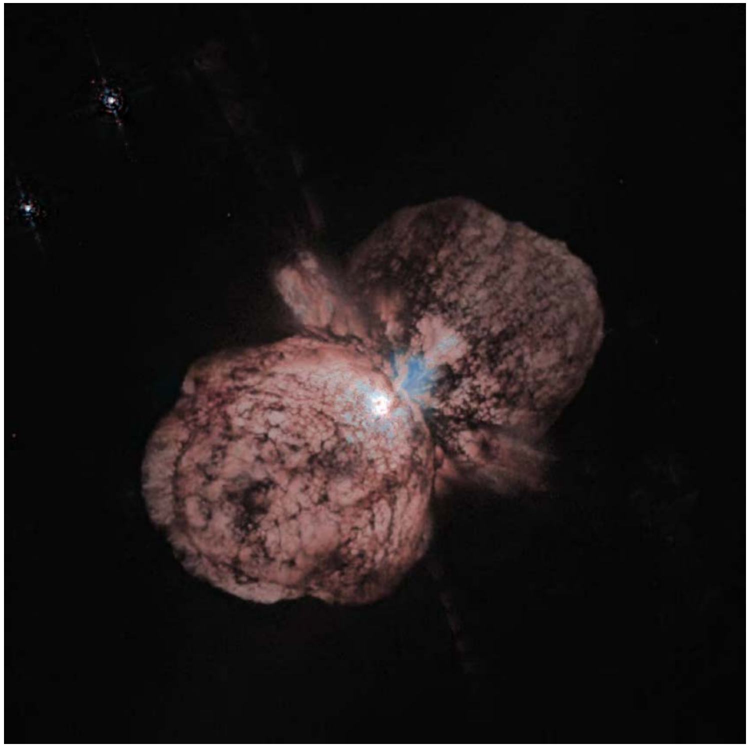
OB

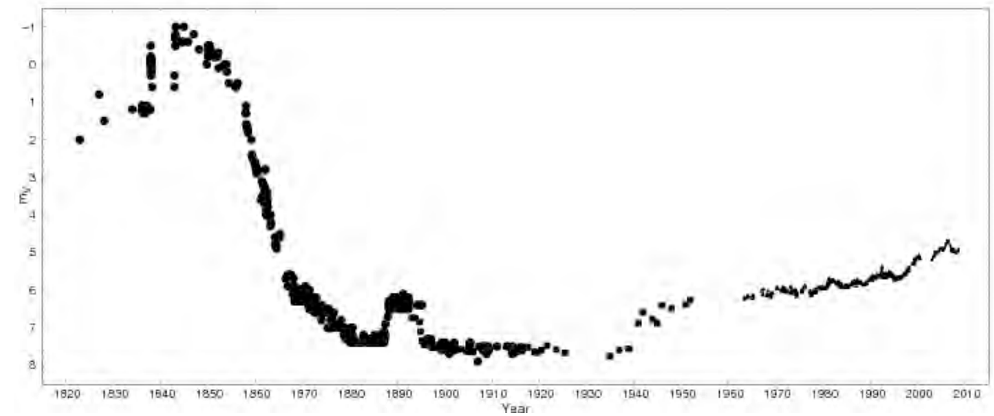
WWC

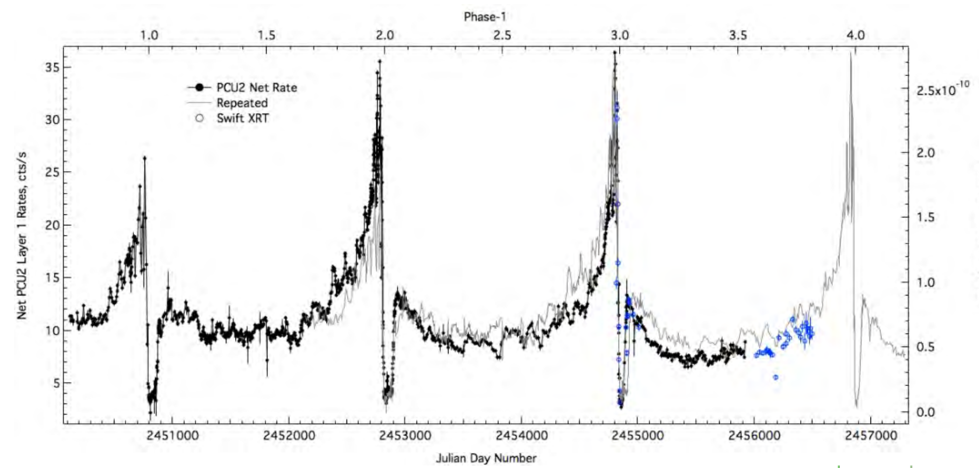
WR



Eta Carinae: LBV and colliding wind system







Very massive binary: LBV+Of star – period 5.5 years and e=0.9.

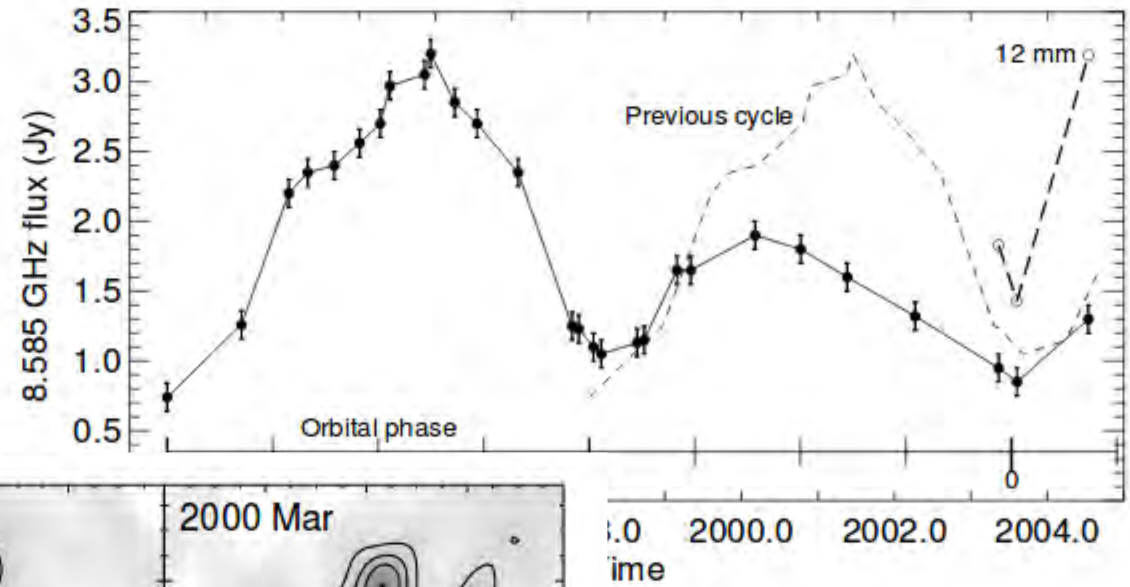
Great eruption 1840.

Period X-ray emission – very peaked around periastron

Eta Car – radio orbital variability

Periodic variability
(White et al 2005)

Hot companion ionises more
of the LBV wind near periastron
(Kashi+Soker 2007)



: at 8.6 GHz, from imaging observa-
ct Array. Recent flux measurements

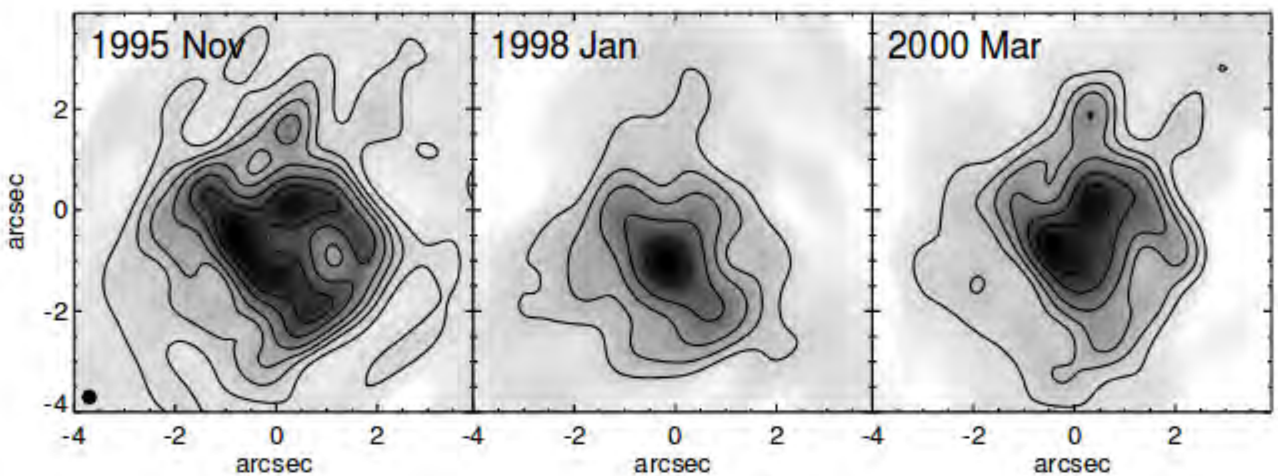


Figure 2. The evolution of the spatial distribution of the radio flux over the 5.5 year cycle. These are 8.6 GHz images from the ATCA with contours at brightness temperatures of 200, 500, 1000, 2000, 4000, 6000 and 8000 K. The image in 1998 was acquired close to the time of the spectroscopic event, and the peak in this image is assumed to be at the location of the stellar system. The beam size is 0.3″ (shown in the lower left corner).

Radio Emission from Magnetic Massive stars: CU Vir

CU Vir: bright MCP star – rapid rotator (0.52 d) – dipolar(ish) kG B-field.

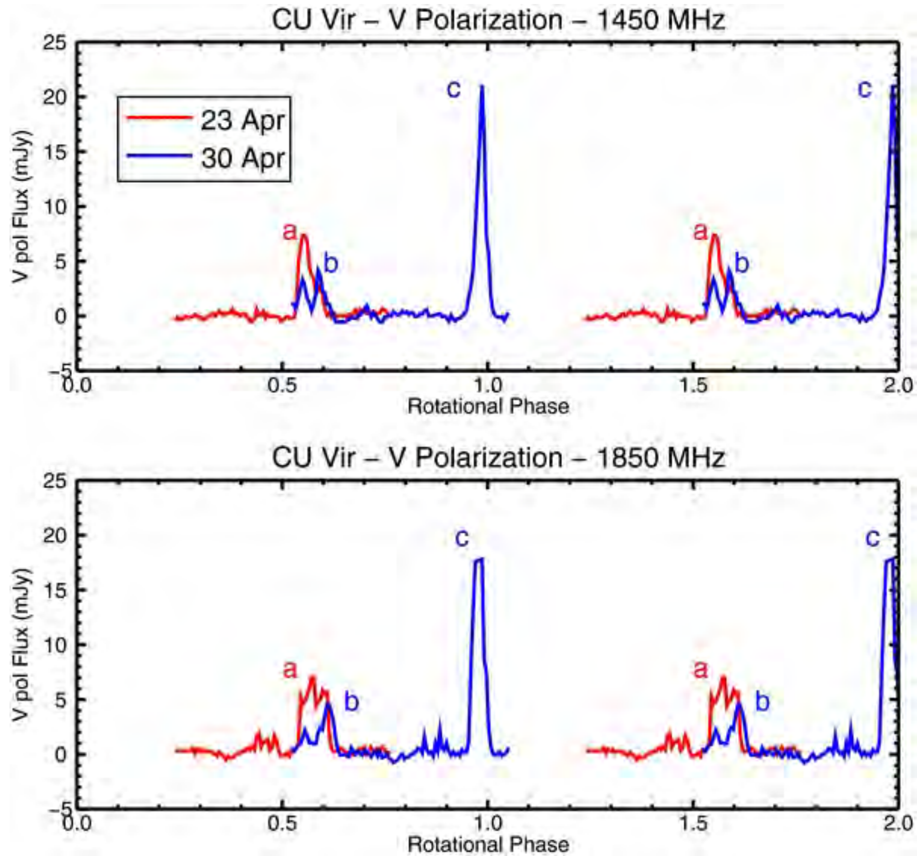
2 radio pulses per rotation – likely ECM emission from polar regions.

For ECM emission to occur we require

$\omega_p/\Omega_e<1$

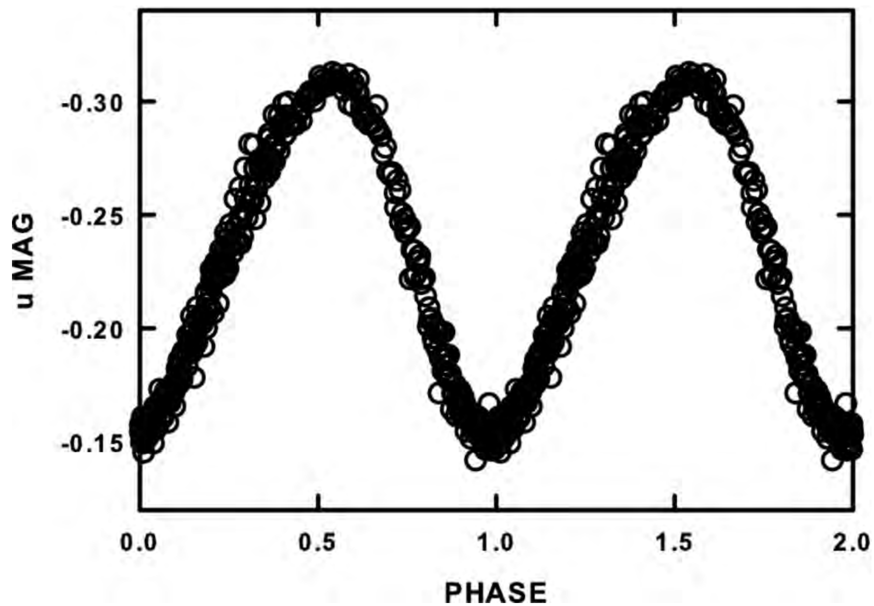
ω_p plasma frequency ~ $n^{1/2}$

Ω_e electron cyclotron frequency ~ B



Trigilio et al. 2011

Radio Emission from Magnetic Massive stars: CU Vir



Optical variations – surface features – and has shown period change ("glitches").

Discrepancy in O-C curve between optical and radio.

How unique is CU Vir?

Radio Recombination Lines (RRLs)

MWC349A – most intense stellar radio continuum at cm wavelengths – B[e] supergiant and UCHII region

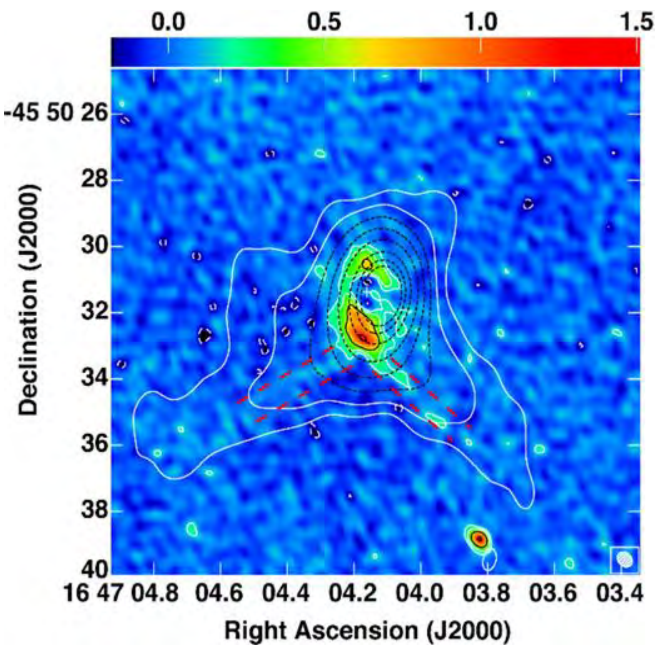
H30α – 232GHz.

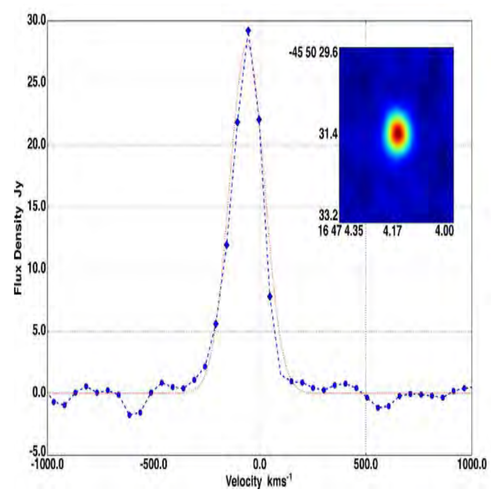
Baez-Rubio et al. 2013

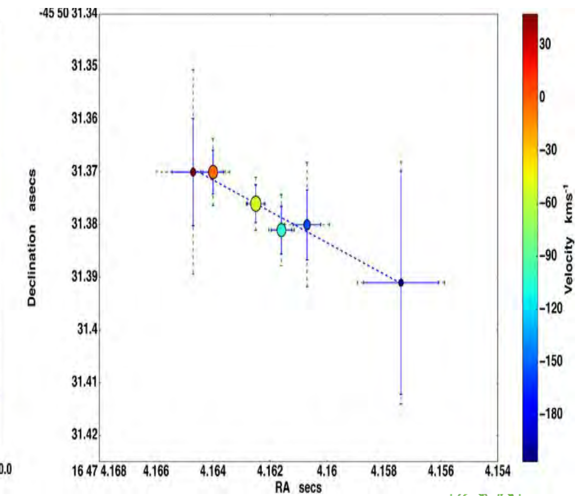
Radio Recombination Lines (RRLs)

Westerlund 1 No.9 – ALMA observations of LBV in star cluster.

Mdot 6.4e-5 Msun/yr (d~5 kpc) and slow wind (50km/s)







ALMA (100GHz)+ 8.4GHz contours.

Fenech et al. (2016)

H41α RRL profile:data+ Gaussian fit

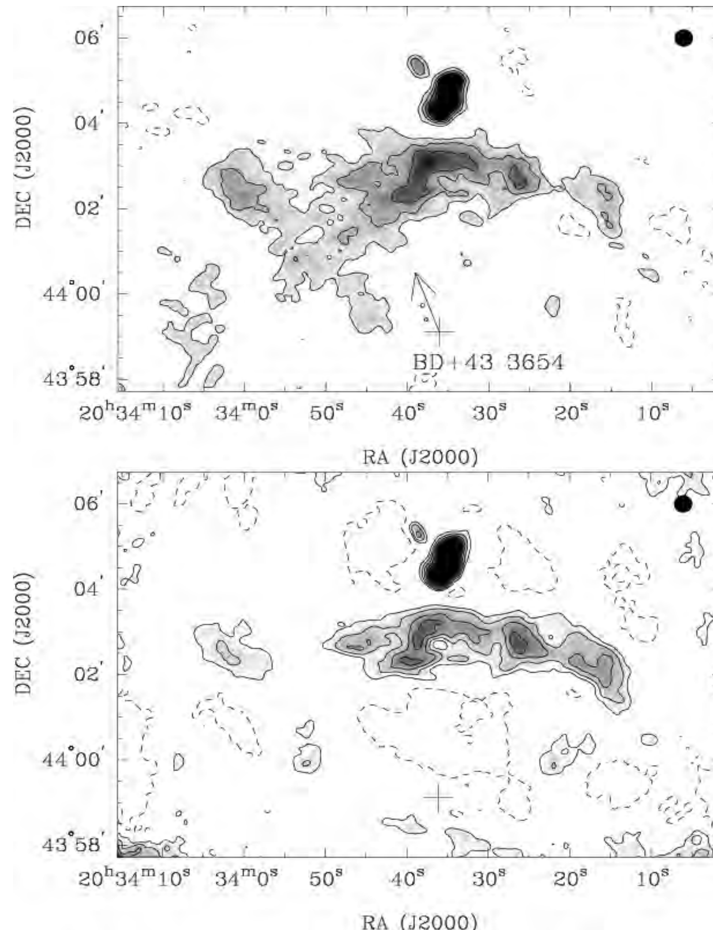
Bow shocks and Runaways

BD+43 3654: O4 supergiant
And runaway star.
Ejected from Cyg OB2

VLA data
1.4GHz (top) and 4.8GHz (bottom).

Mostly thermal emission and good tie up with dust emission in Herschel data.

Benagalia et al. (2010).



Bow shocks and Runaways

Thoughts on the Future

- Magnetic OB stars – can we see variability as the star

rotates – higher frequencies better as we see deeper into the magnetosphere.

- Radio bursts – enormous effort for SKA etc to see bursts (FRBs/transients). Some will be OB stars (and low-mass dwarfs).

- Sensitive low frequency arrays – low frequency turnovers/absorption mechanisms (uGMRT etc).

- Time variability – mostly quite weak sources – variability on flow timescales of the wind (~1 hour).

-Wide-band observations - spectral slope changes – especially at high frequency – evidence of wind acceleration and perhaps clumping.

-Line emission – only rare objects now possible (LBVs -dense winds) – a greater range of objects will be possible.

Thoughts on the Future

Large Galactic Plane Surveys – eg SCORPIO project (Umana et al 2015).

ATCA: 38 pointings (each 1 hour) covering 2 x 0.5 deg^2
Frequency range 1.1-3.1GHz.
Achieved ~30microJy, resolution 10 arcsec – 600 point sources from pilot field (including a number of OB stars).

Low frequency surveys – more extensive surveys and better for non-thermal sources.
High frequency surveys – more expensive in time, but better for thermal sources.

and then onto SKA...

Stratification in Stellar Winds

We also expect time variability in the radio emission as these structure rotate.