The role of pre-supernova massive stars in the acceleration of Galactic Cosmic Rays

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CosPA13 - Gent - June 2023

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What objects are we talking about?

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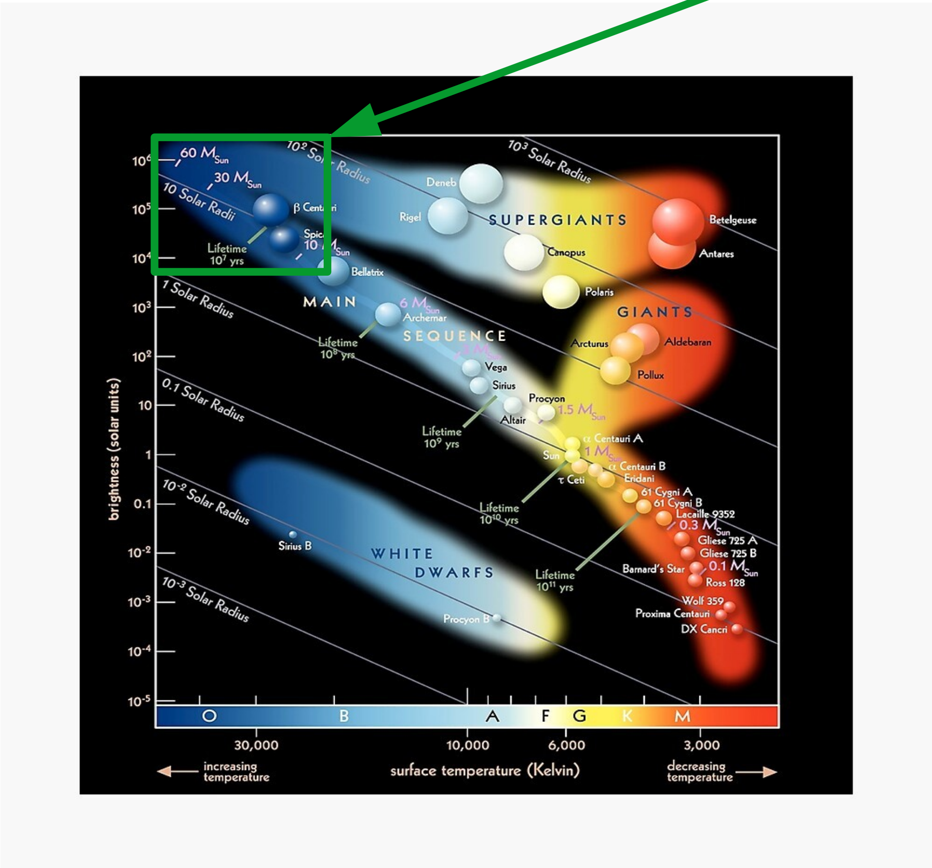

Massive → M > 8–10 M_{sol}

Hot → T > 25000 K

Luminous → L > 10^4 L_{sol} (up to 10^6 L_{sol} !)

Short-lived → t_{evol} < 10 Myr

Rare → f_{popul} ~ 1 ppm

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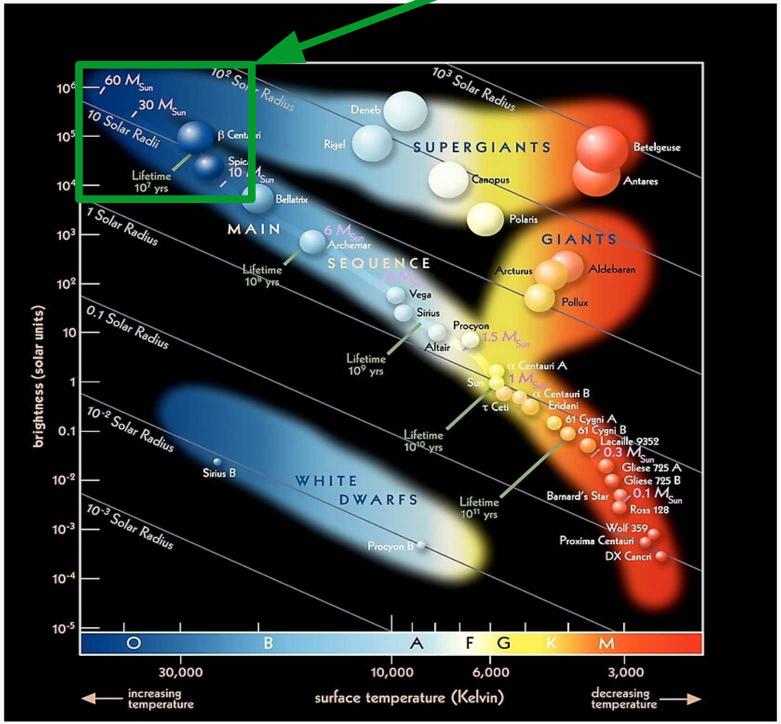

Important feature! → Stellar wind

Continuous outflow of stellar material driven by the strong radiation pressure (*reminder: high luminosity!*)

→ conversion of radiative energy into mechanical energy

Two main properties:

1. Mass loss rate : $10^{-7} - 10^{-5}$ M_{sol}/yr
2. Terminal velocity : 1000 – 3000 km/s

→ Wind kinetic power: $$P_{kin} = \frac{1}{2}\dot{M}V_{\infty}^2$$

Important for energy budget considerations!

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Massive stars end their evolution through a core-collapse supernova episode

Convention adopted here:
"pre-supernova" refers to any evolution stage prior to SN explosion

Various evolution pathways depending on the mass

$M \lesssim 15\,M_\odot$	MS (OB) → RSG (→ BSG in blue loop? → RSG) → SN II mass loss is relatively unimportant, $\lesssim$ few $M_\odot$ is lost during entire evolution
$15\,M_\odot \lesssim M \lesssim 25\,M_\odot$	MS (O) → BSG → RSG → SN II mass loss is strong during the RSG phase, but not strong enough to remove the whole H-rich envelope
$25\,M_\odot \lesssim M \lesssim 40\,M_\odot$	MS (O) → BSG → RSG → WNL → WNE → WC → SN Ib the H-rich envelope is removed during the RSG stage, turning the star into a WR star
$M \gtrsim 40\,M_\odot$	MS (O) → BSG → LBV → WNL → WNE → WC → SN Ib/c an LBV phase blows off the envelope before the RSG can be reached

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All these pathways end with the SN

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Advanced evolution stages are characterized by significantly enhanced mass loss

All these pathways end with the SN

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What about particle acceleration by pre-SN massive stars?

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Basically, particle acceleration consists in *energy transfer to particles from a given energy reservoir…*
→ magneto-hydrodynamic shocks are quite good candidates

"**Diffusive Shock Acceleration (DSA)**" is known to be efficient at converting shock mechanical energy into particle acceleration

(Drury L. O. 1983, Rep. Prog. Phys., 46, 973)

Perfect example →

Supernova remnants (SNRs)

Result of the sudden outflow of stellar material at high speed (up to 10^4 km/s)
→ $E_{kin} \sim 10^{51}$ erg

Believed to be a major source of Galactic Cosmic Rays (GCRs), provided 10–20% of E_{kin} converted into PA

A bit difficult to reach the knee of the CR spectrum (~ PeV)

Active at PA for at most a few 1000 yr (slow down of the shock front)

(Vink J. 2020, Physics and evolution of supernova remnants, A&A Library, Springer)

Efficient source of non-thermal radiation in the **radio** and high energy domains

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What to expect from pre-SN massive stars?

Efficient PA active with high velocity jump during t_{evol}

$P_{kin} \; t_{evol} = E_{kin} \sim 10^{50} – 4 \; 10^{51}$ erg

Efficient PA active for at most a few 1000 yrs

$E_{kin} \sim 10^{51}$ erg

This available kinetic energy in stellar winds needs shocks for DSA to operate and contribute to PA, i.e. one has to identify something the wind could interact with
→ ***various pre-SN configurations deserve to be investigated, and this is a relevant science case for radio astronomy***

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What about the potential particle accelerators among massive stars?

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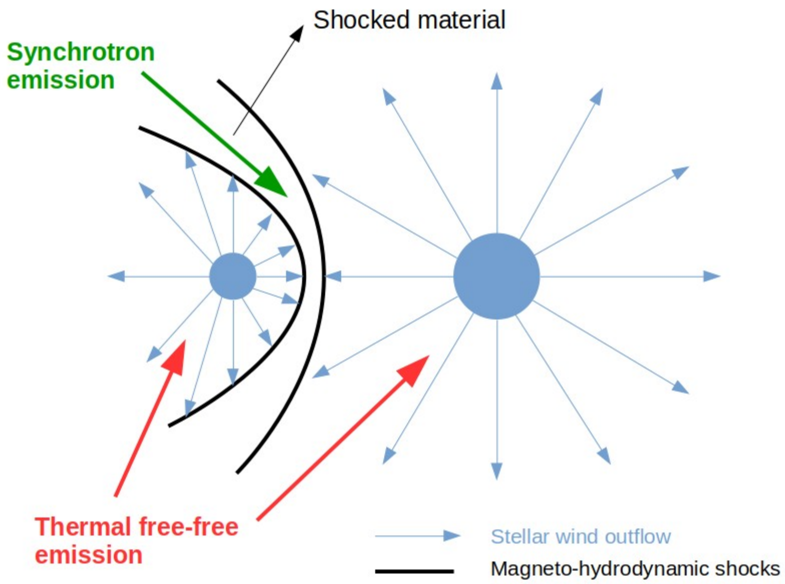
Particle-Accelerating Colliding-Wind Binaries (PACWBs)



Most promising pre-SN configuration!

Requirement: binary (or higher multiplicity) system → ok, most MS are in multiple systems

~ 50 systems identified mainly through radio observations

Census affected by strong biases (free-free absorption, time variability…) → population heavily underestimated

Catalogue of PACWBs:
www.astro.uliege.be/~debecker/pacwb

(De Becker & Raucq 2012, A&A, 558, A28
De Becker et al. 2017 A&A, 600, A47)

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Particle-Accelerating Colliding-Wind Binaries (PACWBs)

Most used observatories...

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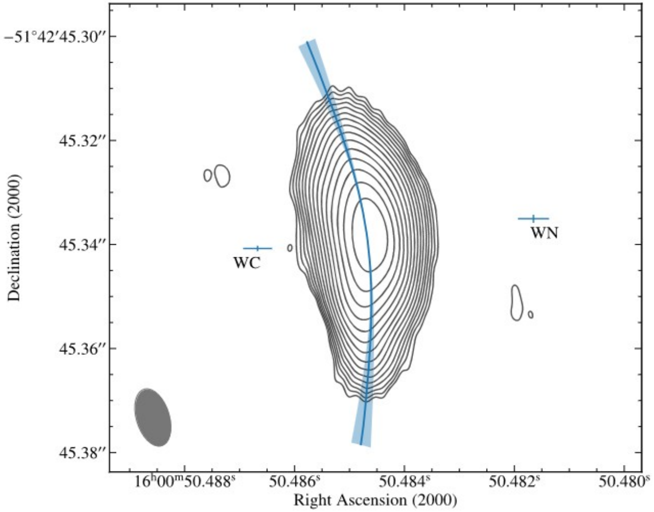
Particle-Accelerating Colliding-Wind Binaries (PACWBs)

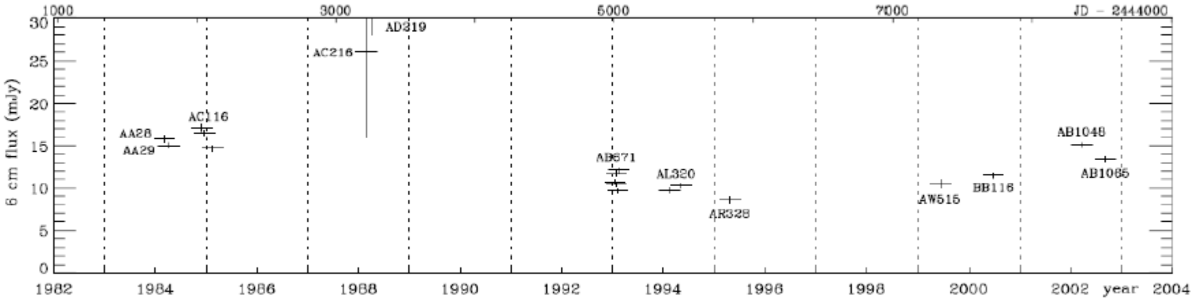
(Blomme et al. 2017 A&A, 501, 2478)

A few results...



Apep: strongest synchrotron emitter (LBA map @2.3 GHz)

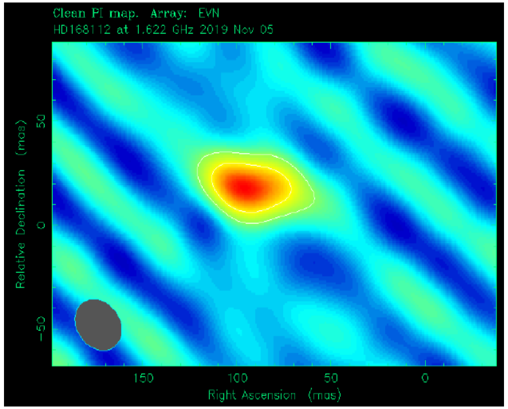
(Marcote et al. 2021 MNRAS, 501, 2478)



HD167971: triple system with a long period of about 21 yr (VLA light curve @6 cm)

HD168112: binary system with undetermined period (first imaging, EVN @18 cm)

(De Becker et al. 2023 in preparation)



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Take away message…

- **Massive stars can contribute to particle acceleration even before the SN explosion (based on energy budget considerations) → potential to contribute to GCRs**
- **Various stellar configurations may be considered, provided significant MHD shock are active**
- **The most promising one is that of Particle-Accelerating Colliding-Wind Binaries (PACWBs)**
- **The census of these particle accelerators relies mainly on radio measurements, and is heavily affected by observational biases**
- **The question of the acceleration of GCRs deserves to consider the combined action of various sources, even though SNRs are likely strong contributors**

Thank you for your attention!

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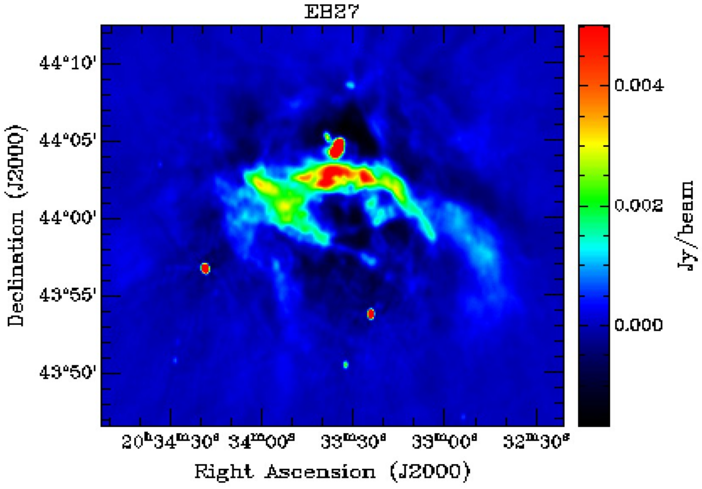
Bow-shock runaways (BSRs)

Massive stars ejected from their birth place
→ traveling in sufficiently dense clouds
→ shock with the ISM

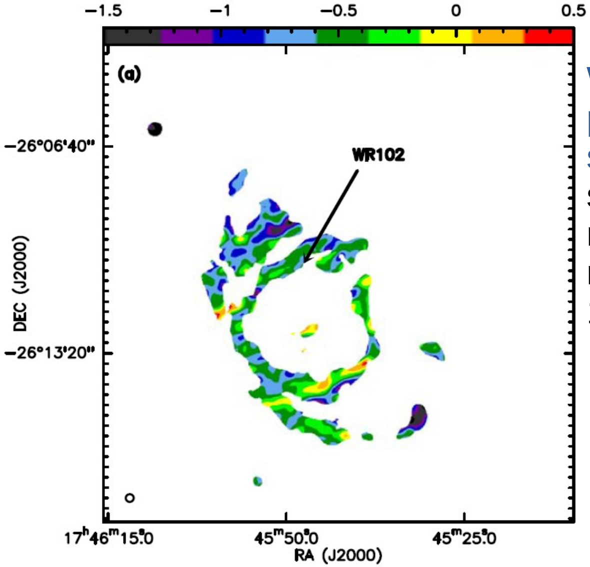


EB27: VLA map @3 GHz

(Benaglia et al. 2021 MNRAS, 503, 2514)

Termination shocks

Strong massive star winds interacting with the surrounding medium
→ shock with the ISM



WR bubble G2.4+1.4 produced by the WO star WR102: GMRT spectral index map made from fluxes measured at 725 and 1250 MHz

(Prajapati et al. 2019 ApJ, 884, 49)