# *VLBI with LOFAR and the EVN to resolve the relativistic outflows from gamma-ray binaries*

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*LOFAR Family Meeting*

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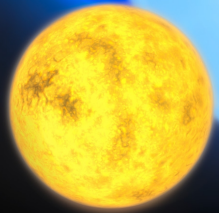
PANTERA Stars

# *Massive stars in the Galaxy…*

*Spectral types of O5–9 or B0*



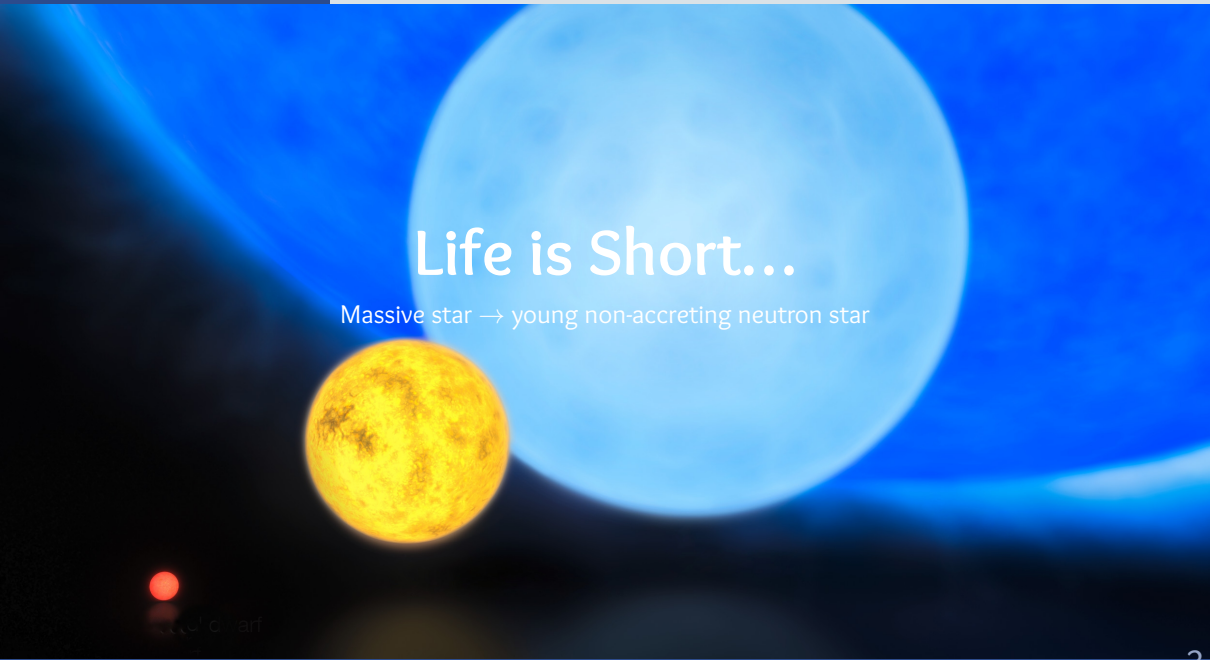
**Mass-loss rates:**

$\dot{M} \sim 10^{-4}$–$10^{-7}$ $M_\odot$ yr$^{-1}$

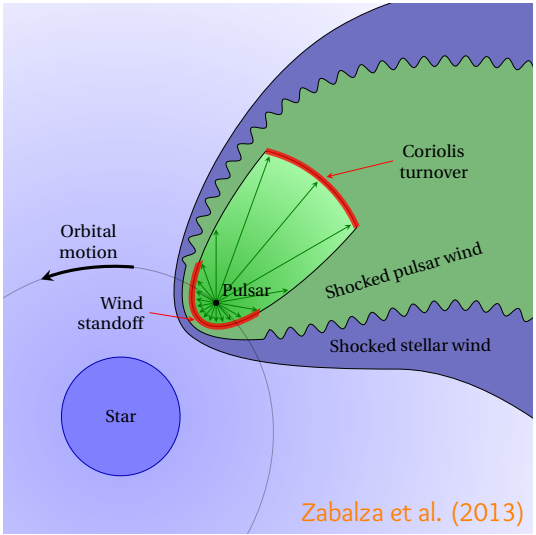
**Stellar wind velocities:**

$v_{\rm winds} \sim 1$—$3 \times 10^3$ km s$^{-1}$

$P_{\rm kinetic} \sim 10^{36–38}$ erg s$^{-1}$


Life is Short...
Massive star → young non-accreting neutron star

# Gamma-ray binaries ($\gamma$Bs)




**Massive star**

With strong winds

+

**Young neutron star**

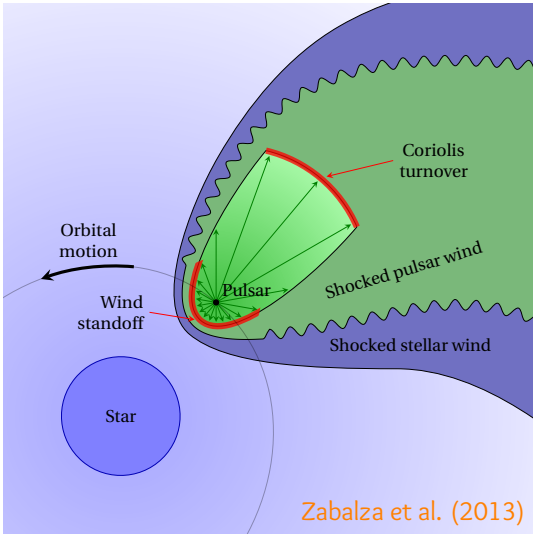
With *relativistic* winds

=

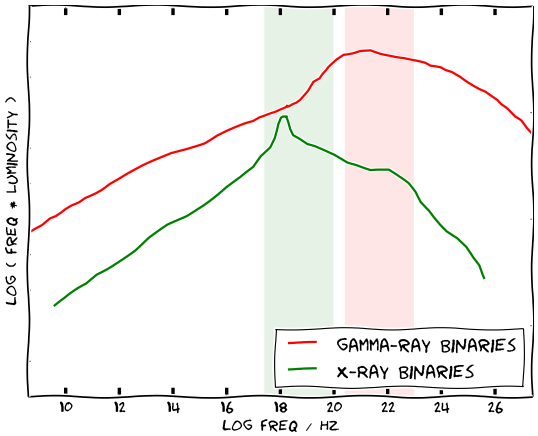
Relativistic shock

Extremely efficient particle acceleration

# Gamma-ray binaries ($\gamma$Bs)

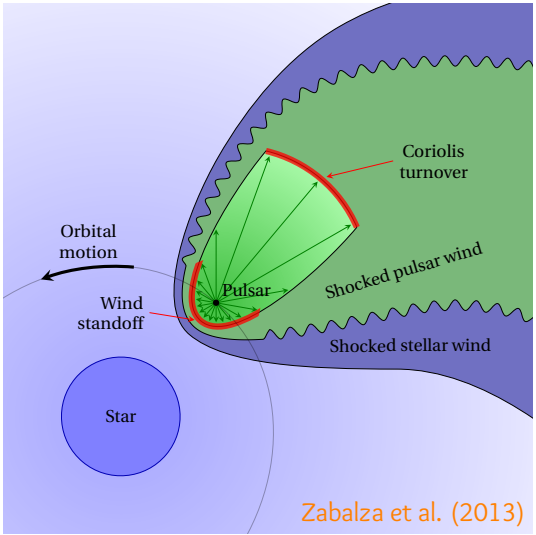



Zabalza et al. (2013)




Non-thermal SED dominated
by the MeV–GeV photons

# Gamma-ray binaries ($\gamma$Bs)



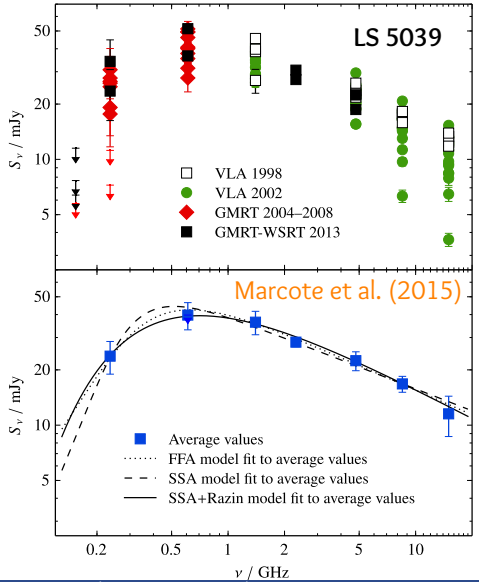

Zabalza et al. (2013)

Only nine systems discovered to date:

| | System | Main star | $P_{orb}$ / days |
|---|---|---|---|
| ⇒ | LS 5039* | O6.5 V | 3.9 |
| | LMC P3 | O5 III | 10.3 |
| | 4FGL J1405.1−6119 | O6.5 III | 13.7 |
| | 1FGL J1018.6−5856 | O6 V | 16.6 |
| ⇒ | LS I +61 303 | B0 Ve | 26.5 |
| | HESS J1832−093 | B8-1.5V | 86.3 |
| | HESS J0632+057 | B0 Vpe | 317.3 |
| | PSR B1259−63 | O9.5 Ve | 1 236.7 |
| | PSR 2032+4127 | B0 Ve | 18 000 |

* confirmed pulsar or neutron star.

# Radio emission from LS 5039 and LS I +61 303



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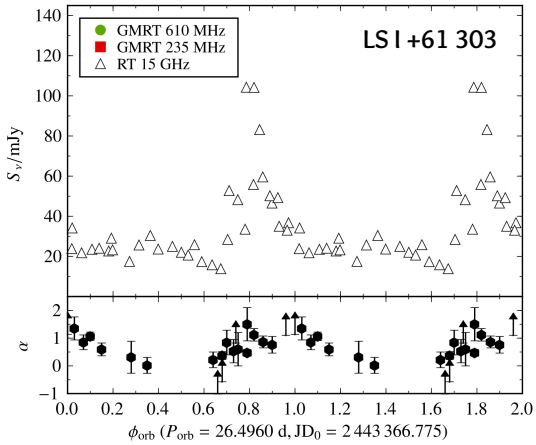


Marcote et al. (2016)

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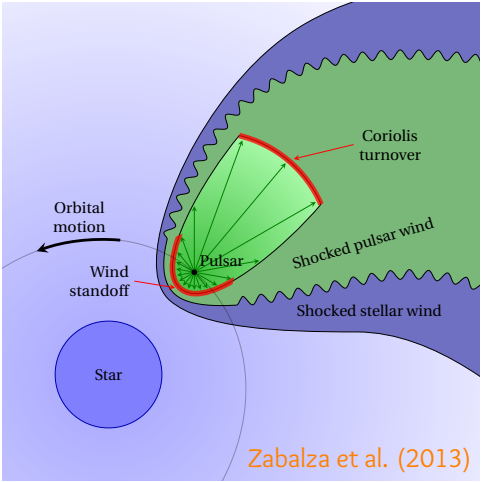
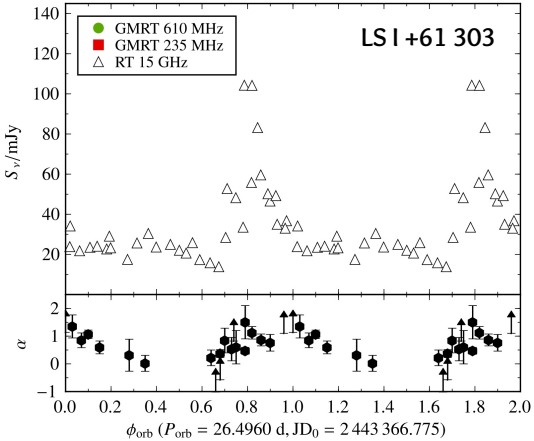



Zabalza et al. (2013)

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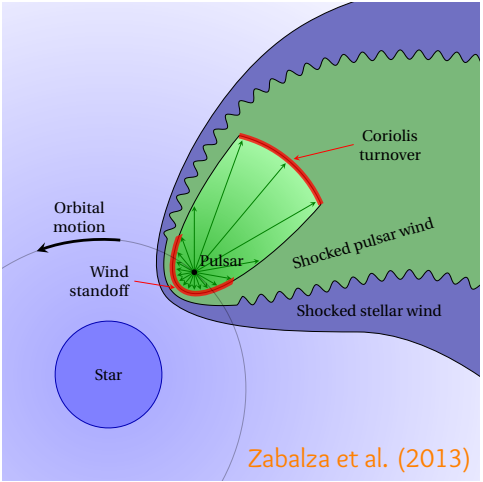


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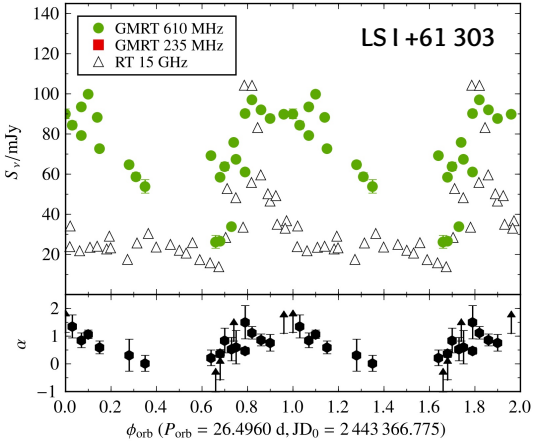


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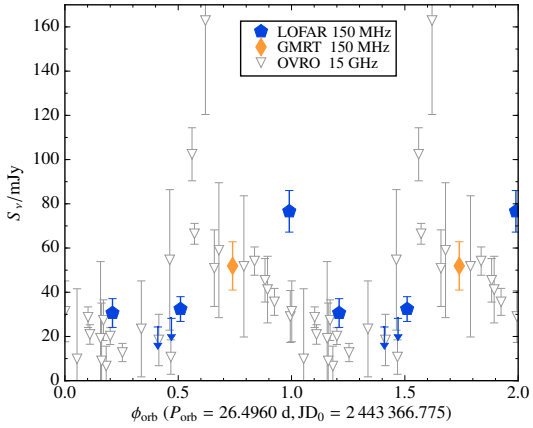
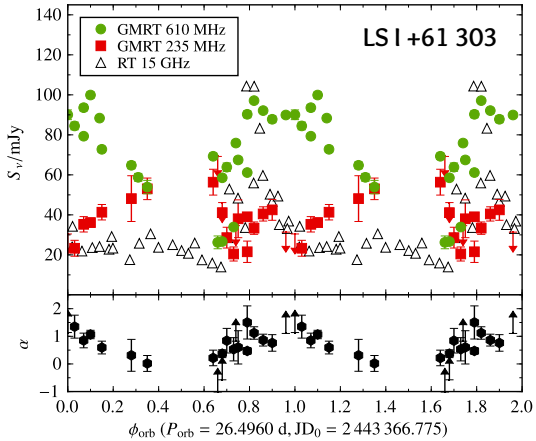



Marcote et al. (2016)

# Emitting region derived for LS I +61 303

**Stellar wind velocity**

$1\,500 \pm 500$ km s$^{-1}$

**Outflow velocity**

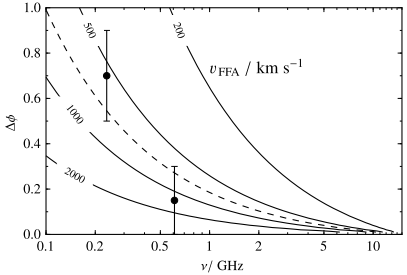
$v_{\rm SSA} = 1\,000 \pm 140$ km s$^{-1}$

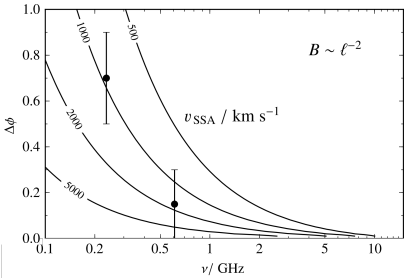
**Emitting region**

Size of $2.4^{+1.7}_{-1.1}$ AU

(semimajor axis of $\sim 0.4$ AU)

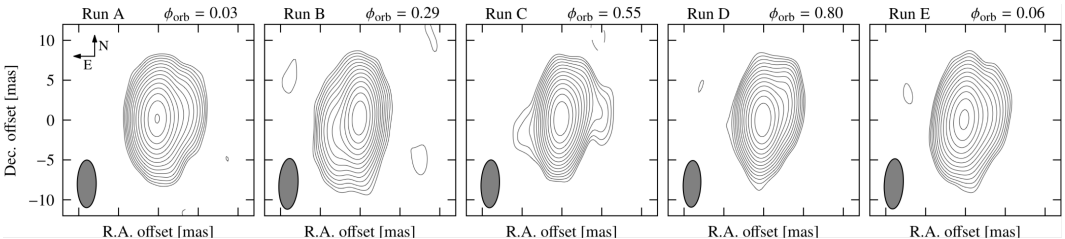
Marcote et al. (2016)



# Tracing the cometary tail of LS 5039

The radio emission is resolved at VLBI (GHz) scales (Moldón et al. 2012)

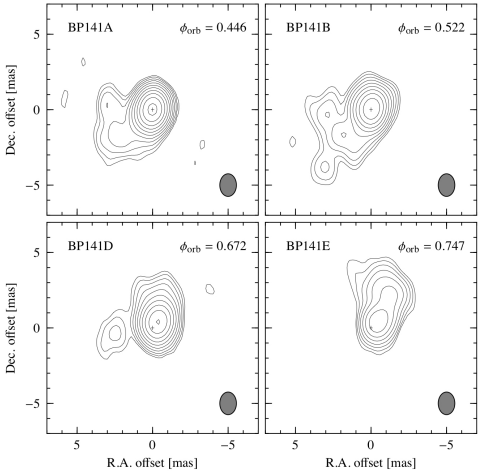



Observations covering one orbital period

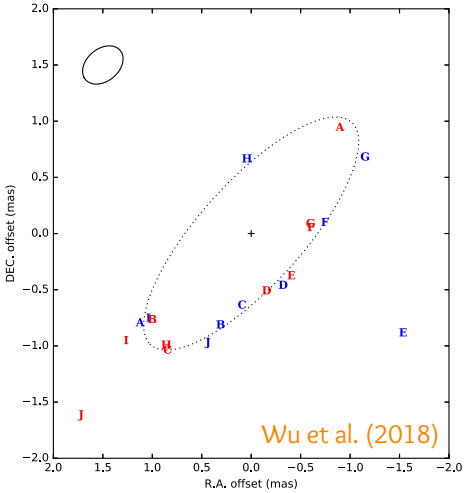
Dominant **core emission** ($\lesssim$ 1 mas, or 3 AU)

**Extended emission** orbitally modulated at mas scales (<10% of the total flux density)

# Tracing the cometary tail of LS I 61 303




Moldón (2012)

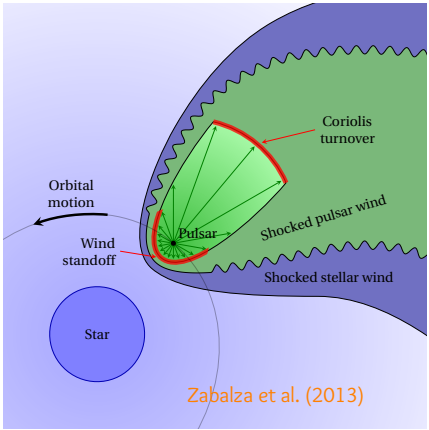


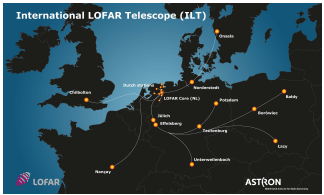

Wu et al. (2018)

# Tracing the radio extended emission


European VLBI Network

Origin of the radio emission?




LOFAR–VLBI

Nebula around the system?

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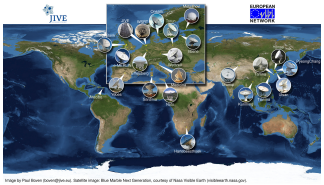


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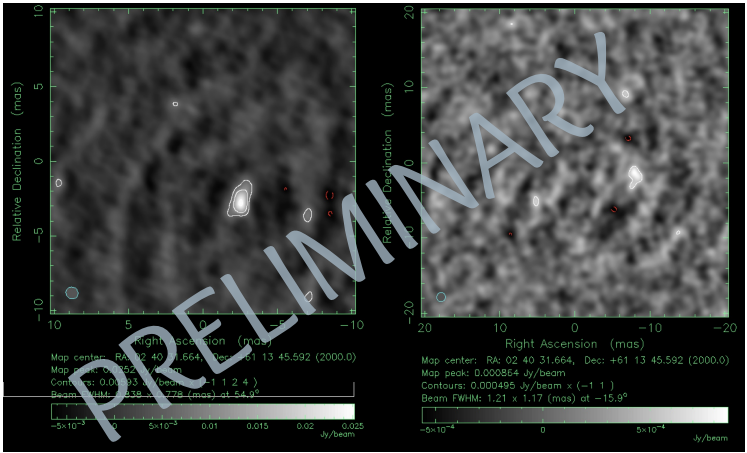

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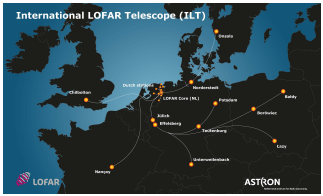


LOFAR–VLBI

Nebula around the system?

**Predicted nebula/halo around the system**

Sizes of tens of AU ($\sim$ 0.1–1 arcsec)?

Flux densities of $\sim$ 0.1–1 mJy?

# Take home messages

$\gamma$-ray binaries are **highly-efficient particle accelerators** and strong non-thermal radio emitters.

The 0.1–10 GHz emission is key to unveil the origin of the radio emission and constrain the simulations.

**VLBI allows us to resolve the full radio emitting region**. Perfect EVN + LOFAR-VLBI tandem.

LOFAR-VLBI or likely **LOFAR v2.0** to unveil the predicted halo?

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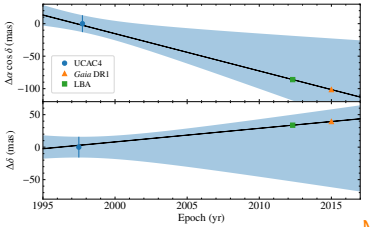
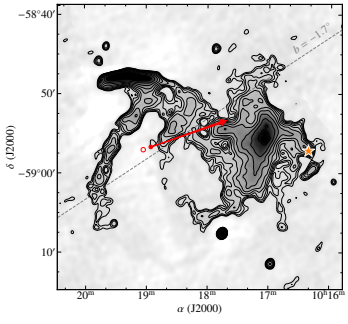
Thanks!

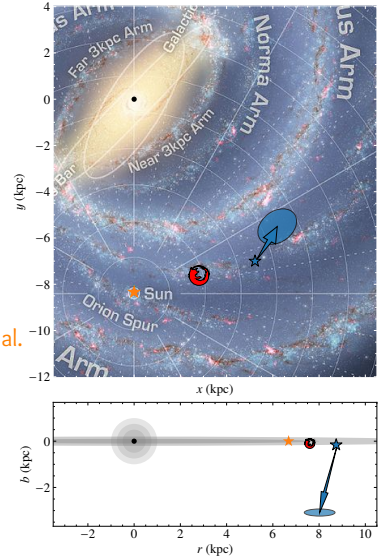
# 1FGL J1018.6−5856 on milliarcsecond (AU) scales




Marcote et al. (2018)

Carretero-Castrillo et al. (in prep)



# Modeling the LS 5039 spectrum

Coherent picture from fits and $\tau_\nu^{\mathrm{FF}}$

- Avg. spectrum: SSA+Razin
- July 19 spectrum: SSA
- July 21 spectrum: SSA+Razin

- Coherent picture with:

$$\ell \sim 0.85 \text{ mas } (\sim 2.5 \text{ AU})$$
$$B \sim 20 \text{ mG}$$
$$n_e \sim 4 \times 10^5 \text{ cm}^{-3}$$
$$\dot{M} \sim 5 \times 10^{-8} \text{ M}_\odot \text{ yr}^{-1}$$