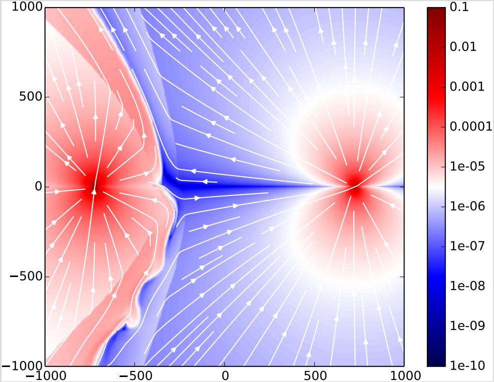
Particle Acceleration and Emission in γ^2 Velorum.



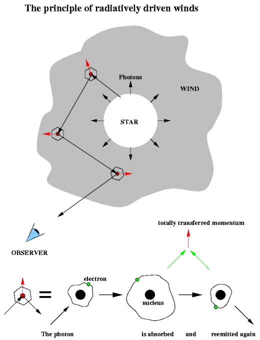
R. Kissmann

universität innsbruck

Binary System

- Two Massive Stars. . .

Line-driven Winds



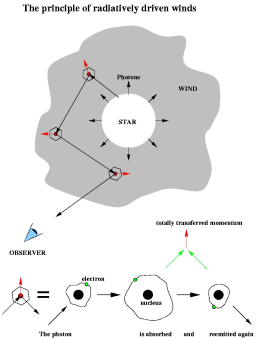
(Sketch by R. Kudritzki)

Binary System

- Two Massive Stars. . .
- . . . each with line-driven wind outflow

Particle Acceleration in CWBs

Line-driven Winds



(Sketch by R. Kudritzki)

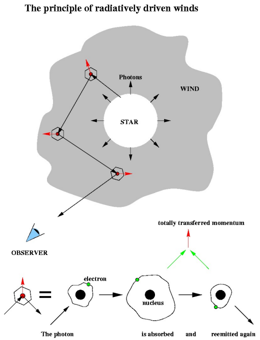
Binary System

- Two Massive Stars...
- ...each with line-driven wind outflow

Results

- Supersonic massive wind outflows
- Interaction → wind-collision region

Line-driven Winds



(Sketch by R. Kudritzki)

Binary System

- Two Massive Stars. . .
- . . . each with line-driven wind outflow

Results

- Supersonic massive wind outflows
- Interaction → wind-collision region

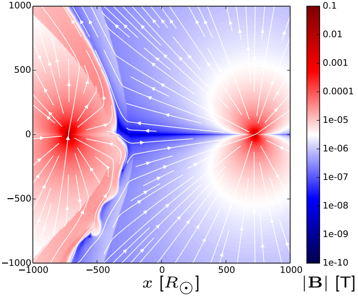
Particles

- Shock Acceleration
- Interaction with matter
  → gamma rays

1: MHD Solver

- Line-driven winds
- Stellar dipole fields
- Free evolution

Magnetic Field



(RK et al. (2016) ApJ **831**, 121)

CWBs: Our Modelling Ingredients

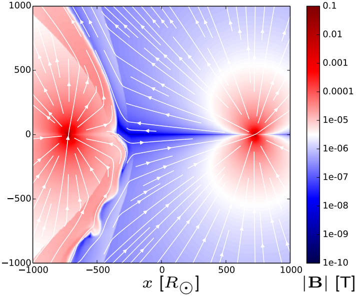
1: MHD Solver

- Line-driven winds
- Stellar dipole fields
- Free evolution

2: Energetic Particles

- Injection at Shocks
- Solution of Parker-transport equation

Magnetic Field



(RK et al. (2016) ApJ **831**, 121)

CWBs: Our Modelling Ingredients

1: MHD Solver

- Line-driven winds
- Stellar dipole fields
- Free evolution

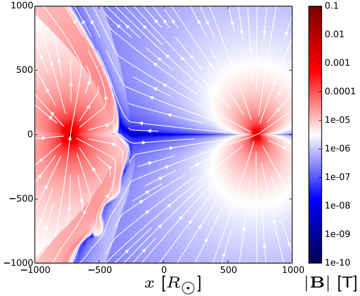
2: Energetic Particles

- Injection at Shocks
- Solution of Parker-transport equation

3: Non-Thermal Emission

- Computation From Particle Spectra
- Postprocessing

Magnetic Field



(RK et al. (2016) ApJ **831**, 121)

Stellar Winds

- Example: Hydrodynamics

System of Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u} + p \mathbb{1}) = 0$$

$$\frac{\partial e}{\partial t} + \nabla \cdot ((e + p)\, \mathbf{u}) = 0$$

Stellar Winds

- Example: Hydrodynamics
- Radiative cooling

System of Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u} + p\mathbb{1}) = 0$$

$$\frac{\partial e}{\partial t} + \nabla \cdot ((e + p)\, \mathbf{u}) = S_e$$

Stellar Winds

- Example: Hydrodynamics
- Radiative cooling
- Force density $\mathbf{f}$:
  - Gravity of stars
  - Radiative Driving

System of Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u} + p\mathbb{1}) = \mathbf{f}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot ((e + p)\,\mathbf{u}) = S_e + \mathbf{u} \cdot \mathbf{f}$$

Force density

$$\mathbf{f} = \rho \sum_{i=1}^{n} \left(-GM_{\star,i} \frac{\mathbf{r}_i}{r_i^3} + \mathbf{g}^{l}_{rad,i} + \mathbf{g}^{e}_{rad,i} \right)$$

universität innsbruck

Stellar Winds

- Example: Hydrodynamics
- Radiative cooling
- Force density $\mathbf{f}$:
  - Gravity of stars
  - Radiative Driving
- Radiative Driving:
  - Scattering off free electrons

System of Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u} + p\mathbb{1}) = \mathbf{f}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot ((e + p)\, \mathbf{u}) = S_e + \mathbf{u} \cdot \mathbf{f}$$

Effect of Electrons

$$\mathbf{g}^{e}_{rad,i} = \frac{\sigma_e L_{\star,i}}{4\pi r_i^2 c} \mathbf{e}_{r_i}$$

Force density

$$\mathbf{f} = \rho \sum_{i=1}^{n} \left(-G M_{\star,i} \frac{\mathbf{r}_i}{r_i^3} + \mathbf{g}^{l}_{rad,i} + \mathbf{g}^{e}_{rad,i} \right)$$

Stellar Winds

- Example: Hydrodynamics
- Radiative cooling
- Force density $\mathbf{f}$:
  - Gravity of stars
  - Radiative Driving
- Radiative Driving:
  - Scattering off free electrons
  - Line driving

System of Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u} + p\mathbb{1}) = \mathbf{f}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot ((e+p)\,\mathbf{u}) = S_e + \mathbf{u} \cdot \mathbf{f}$$

Effect of Electrons

$$\mathbf{g}^{e}_{rad,i} = \frac{\sigma_e L_{\star,i}}{4\pi r_i^2 c} \mathbf{e}_{r_i}$$

Force density

$$\mathbf{f} = \rho \sum_{i=1}^{n} \left(-GM_{\star,i} \frac{\mathbf{r}_i}{r_i^3} + \mathbf{g}^{l}_{rad,i} + \mathbf{g}^{e}_{rad,i} \right)$$

Acceleration by Lines

$$\mathbf{g}^{l}_{rad,i} = \frac{\sigma_e}{c} \frac{L_{\star,i}}{4\pi r_i^2} k t^{-\alpha} I_{FD} \mathbf{e}_{r_i}$$

Line Driving

- Contribution of $> 10^4$ lines
- Wind expansion $\rightarrow$ Doppler

$\rightarrow$ Expensive

universität innsbruck

Line Driving

- Contribution of $> 10^4$ lines
- Wind expansion $\rightarrow$ Doppler

$\rightarrow$ Expensive

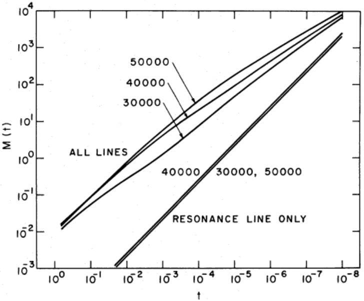
Numerical Approximation

- Collective: power law

Resulting Acceleration

$$\mathbf{g}^{l}_{rad,i} = \frac{\sigma_e}{c}\frac{L_{\star,i}}{4\pi r_i^2} k t^{-\alpha} I_{FD} \mathbf{e}_{r_i}$$

Dependence on Optical Depth



(Castor, Abbot, & Klein ApJ **195**, 157)

universität innsbruck

Line Driving

- Contribution of $> 10^4$ lines
- Wind expansion $\rightarrow$ Doppler

$\rightarrow$ Expensive

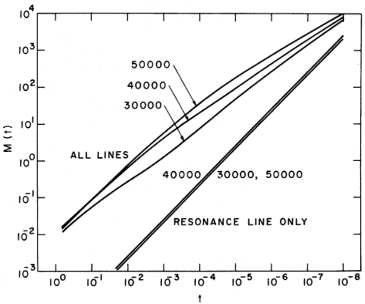
Numerical Approximation

- Collective: power law
- Dependence on optical depth t

Resulting Acceleration

$$\mathbf{g}^{l}_{rad,i} = \frac{\sigma_e}{c}\frac{L_{\star,i}}{4\pi r_i^2} k t^{-\alpha} I_{FD} \mathbf{e}_{r_i}$$

Dependence on Optical Depth



(Castor, Abbot, & Klein ApJ **195**, 157)

Optical Depth

$$t = \sigma_e \rho v_{th} \left|\frac{du}{dr}\right|^{-1}$$

universität innsbruck

Line Driving

- Contribution of $> 10^4$ lines
- Wind expansion $\rightarrow$ Doppler

$\rightarrow$ Expensive

Numerical Approximation

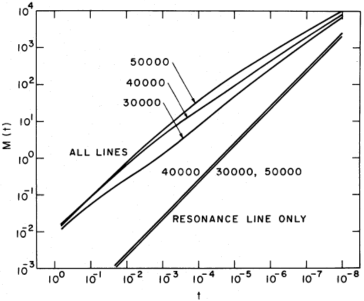
- Collective: power law
- Dependence on optical depth t

$\rightarrow$ Velocity gradient

Resulting Acceleration

$$\mathbf{g}^{l}_{rad,i} = \frac{\sigma_e}{c} \frac{L_{\star,i}}{4\pi r_i^2} k t^{-\alpha} I_{FD} \mathbf{e}_{r_i}$$

Dependence on Optical Depth



(Castor, Abbot, & Klein ApJ **195**, 157)

Optical Depth

$$t = \sigma_e \rho v_{th} \left| \frac{du}{dr} \right|^{-1}$$

universität innsbruck

Line Driving

- Contribution of $> 10^4$ lines
- Wind expansion $\rightarrow$ Doppler

$\rightarrow$ Expensive

Numerical Approximation

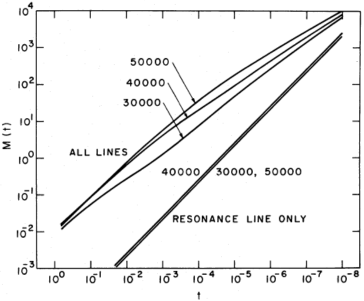
- Collective: power law
- Dependence on optical depth t

$\rightarrow$ Velocity gradient

Resulting Acceleration

$$\mathbf{g}^{l}_{rad,i} = \frac{\sigma_e}{c} \frac{L_{\star,i}}{4\pi r_i^2} k t^{-\alpha} I_{FD} \mathbf{e}_{r_i}$$

Dependence on Optical Depth



(Castor, Abbot, & Klein ApJ **195**, 157)

Optical Depth

$$t = \sigma_e \rho v_{th} \left| \frac{du}{dr} \right|^{-1}$$

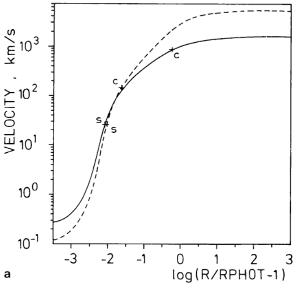
Line Driven Winds

- Very rapid acceleration
- Acceleration rate $\leftrightarrow$ velocity gradient

Line Driven Winds

- Very rapid acceleration
- Acceleration rate ↔ velocity gradient

Wind Velocity



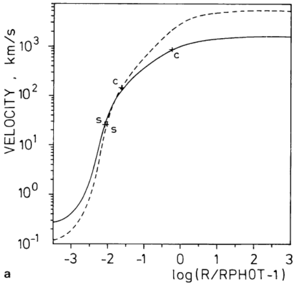
(Castor, Abbot, & Klein ApJ **195**, 157)

universität innsbruck

Line Driven Winds

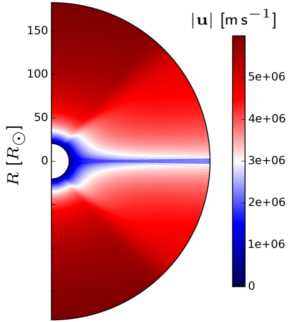
- Very rapid acceleration
- Acceleration rate ↔ velocity gradient
- Magnetic field

Wind Velocity



(Castor, Abbot, & Klein ApJ **195**, 157)

Modified Velocity Field



(RK et al. (2016) ApJ **831**, 121)

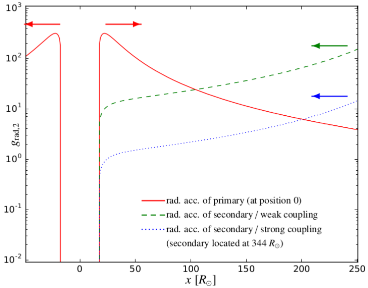
Situation in WR 11

- Collision before v_∞ is reached

Situation in WR 11

- Collision before v_∞ is reached
- Coupling of winds to stellar radiation? (k & α)

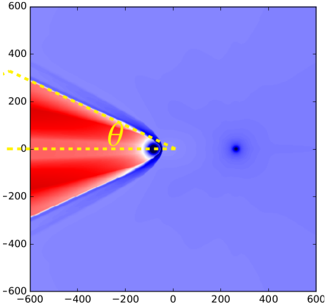
Apastron Configuration



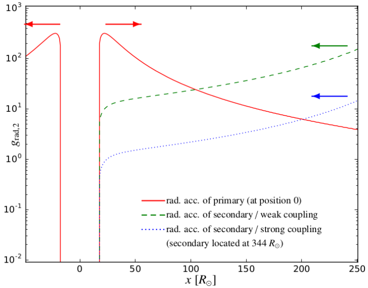
Situation in WR 11

- Collision before v_∞ is reached
- Coupling of winds to stellar radiation? (k & α)

Velocity (Weak Coupling)



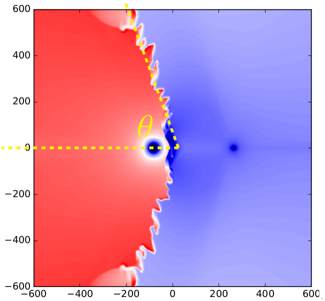
Apastron Configuration



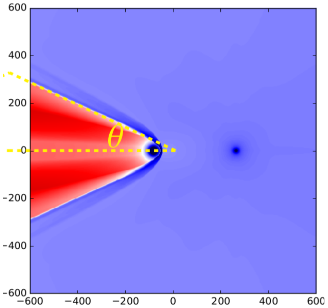
Situation in WR 11

- Collision before v_∞ is reached
- Coupling of winds to stellar radiation? (k & α)

Velocity (Strong Coupling)



Velocity (Weak Coupling)

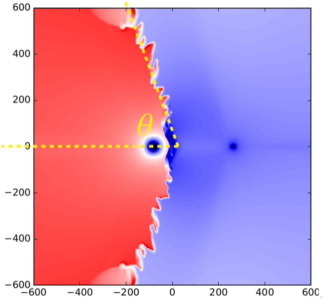


universität innsbruck

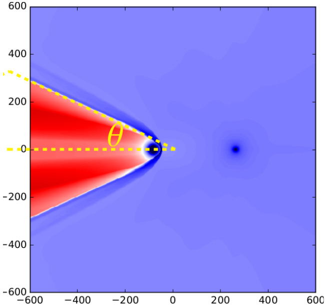
Situation in WR 11

- Collision before v_∞ is reached
- Coupling of winds to stellar radiation? (k & α)

Velocity (Strong Coupling)

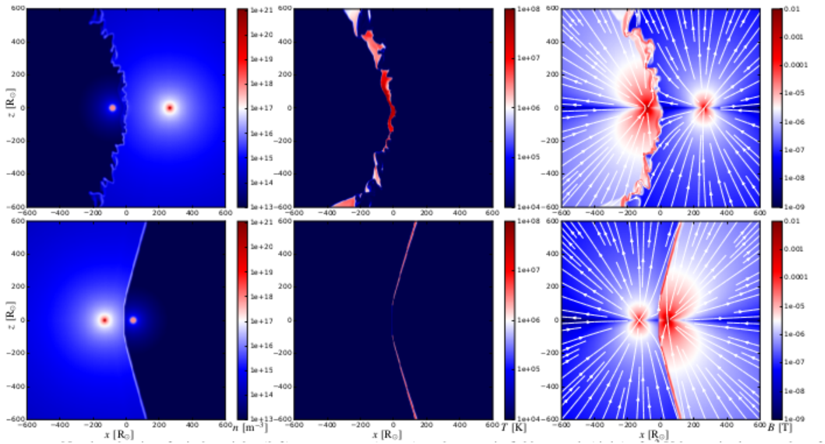


Velocity (Weak Coupling)



Effects

- Radiative breaking
- Shadowing


z [R⊙]
x [R⊙]
n [m⁻³]
T [K]
B [T]
1e+21
1e+20
1e+19
1e+18
1e+17
1e+16
1e+15
1e+14
1e+13
1e+08
1e+07
1e+06
1e+05
1e+04
0.01
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
1e-09

Transport Equation

$$\frac{\partial j}{\partial t} - D(E)\nabla^2 j + \nabla \cdot (\mathbf{u} j) - \frac{\partial}{\partial E}\left(\left(\frac{E}{3}\nabla \cdot \mathbf{u} + \dot{E}_{\mathsf{loss}}\right) j\right) = Q_0 \delta(E - E_0)$$

universität innsbruck

Transport Equation

$$\frac{\partial j}{\partial t} - D(E)\nabla^2 j + \nabla\cdot(\mathbf{u}j) - \frac{\partial}{\partial E}\left(\left(\frac{E}{3}\nabla\cdot\mathbf{u} + \dot{E}_{\mathsf{loss}}\right) j\right) = Q_0\delta(E - E_0)$$

Physical Processes

- Injection at shock fronts
- Advection with fluid flow
- Spatial diffusion
- Energy losses

universität innsbruck

Transport Equation

$$\frac{\partial j}{\partial t} - D(E)\nabla^2 j + \nabla \cdot (\mathbf{u} j) - \frac{\partial}{\partial E}\left(\left(\frac{E}{3}\nabla \cdot \mathbf{u} + \dot{E}_{\text{loss}}\right) j\right) = Q_0 \delta(E - E_0)$$

Physical Processes

- Injection at shock fronts
- Advection with fluid flow
- Spatial diffusion
- Energy losses

Specifics: Adding Particles

Transport Equation

$$\frac{\partial j}{\partial t} - D(E)\nabla^2 j + \nabla \cdot (\mathbf{u} j) - \frac{\partial}{\partial E}\left(\left(\frac{E}{3}\nabla \cdot \mathbf{u} + \dot{E}_{\text{loss}}\right) j\right) = Q_0 \delta(E - E_0)$$

Physical Processes

- Injection at shock fronts
- Advection with fluid flow
- Spatial diffusion
- Energy losses

universität innsbruck

Transport Equation

$$\frac{\partial j}{\partial t} - D(E)\nabla^2 j + \nabla \cdot (\mathbf{u}j) - \frac{\partial}{\partial E}\left(\left(\frac{E}{3}\nabla \cdot \mathbf{u} + \dot{E}_{\text{loss}}\right) j\right) = Q_0 \delta(E - E_0)$$

Physical Processes

- Injection at shock fronts
- Advection with fluid flow
- Spatial diffusion
- Energy losses

Transport Equation

$$\frac{\partial j}{\partial t} - D(E)\nabla^2 j + \nabla\cdot(\mathbf{u}j) - \frac{\partial}{\partial E}\left(\left(\frac{E}{3}\nabla\cdot\mathbf{u} + \dot{E}_{\text{loss}}\right)j\right) = Q_0\delta(E-E_0)$$

Energy loss processes

- Synchrotron (Electrons)
- Inverse Compton (Electrons)
- Thermal bremsstrahlung (Electrons)
- Coulomb losses
- Nucleon-nucleon interaction

Physical Processes

- Injection at shock fronts
- Advection with fluid flow
- Spatial diffusion
- Energy losses

Specifics: Adding Particles

universität innsbruck

Transport Equation

$$\frac{\partial j}{\partial t} - D(E)\nabla^2 j + \nabla \cdot (\mathbf{u} j) - \frac{\partial}{\partial E}\left(\left(\frac{E}{3}\nabla \cdot \mathbf{u} + \dot{E}_{\text{loss}}\right) j\right) = Q_0 \delta(E - E_0)$$

Implementation

- Electrons & Protons

→ Advected scalar fields

→ Semi-Lagrangian solver

Physical Processes

- Injection at shock fronts
- Advection with fluid flow
- Spatial diffusion
- Energy losses

Specifics: Adding Particles

Transport Equation

$$\frac{\partial j}{\partial t} - D(E)\nabla^2 j + \nabla \cdot (\mathbf{u}j) - \frac{\partial}{\partial E}\left(\left(\frac{E}{3}\nabla \cdot \mathbf{u} + \dot{E}_{\text{loss}}\right) j\right) = Q_0 \delta(E - E_0)$$

Implementation

- Electrons & Protons

→ Advected scalar fields

→ Semi-Lagrangian solver

Physical Processes

- Injection at shock fronts
- Advection with fluid flow
- Spatial diffusion
- Energy losses

Specifics: Adding Particles

Transport Equation

$$\frac{\partial j}{\partial t} - D(E)\nabla^2 j + \nabla \cdot (\mathbf{u}j) - \frac{\partial}{\partial E}\left(\left(\frac{E}{3}\nabla \cdot \mathbf{u} + \dot{E}_{\text{loss}}\right) j\right) = Q_0 \delta(E - E_0)$$

Implementation

- Electrons & Protons
- → Advected scalar fields
- → Semi-Lagrangian solver

Physical Processes

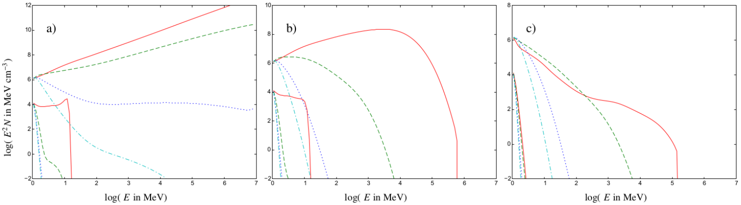
- Injection at shock fronts
- Advection with fluid flow
- Spatial diffusion
- Energy losses

Results

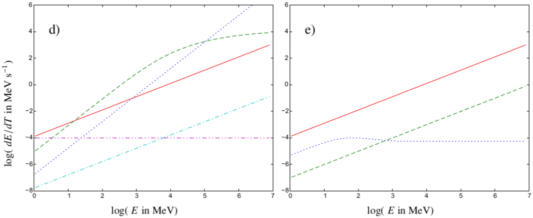
- Position-dependent particle flux
- → Can compute non-thermal emission

universität innsbruck

Particle Spectra

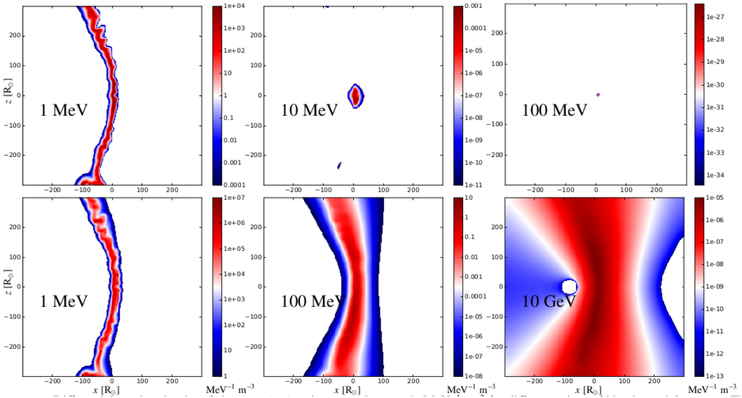


Energy-Loss and Acceleration Rates

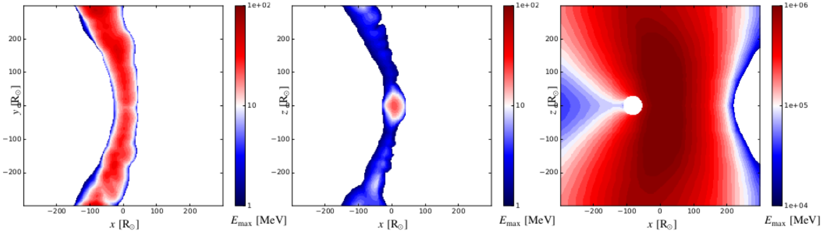


Resulting Particle Distribution

Spatial Distribution

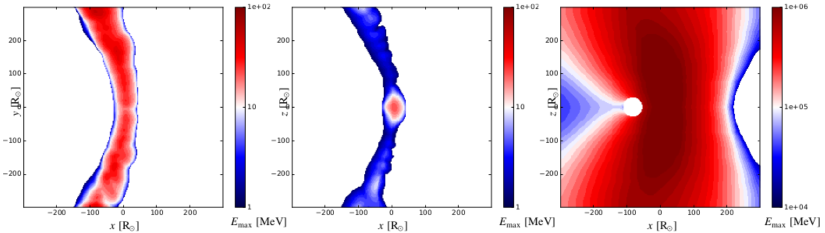


Maximum Particle Energies

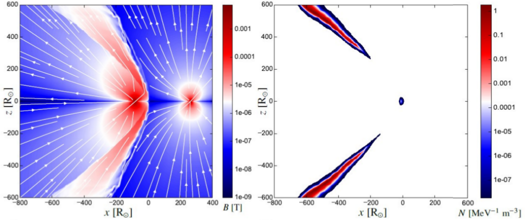


universität innsbruck

Maximum Particle Energies



Magnetic Field & Synchrotron Losses



Properties of WR 11

- Electrons Suppressed:
  - High radiation fields
  - Strong magnetic field

Properties of WR 11

- Electrons Suppressed:
  - High radiation fields
  - Strong magnetic field
- Dominant Process:

$\rightarrow \; p + p \rightarrow p + p + \pi^0$

$\rightarrow \; \pi^0 \rightarrow \gamma + \gamma$

Gamma-Ray Emission I

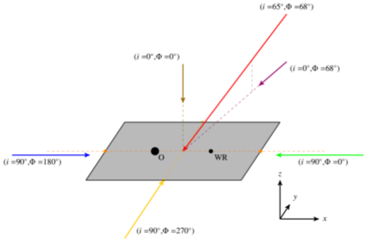
Properties of WR 11

- Electrons Suppressed:
  - High radiation fields
  - Strong magnetic field
- Dominant Process:

$\rightarrow \; p + p \rightarrow p + p + \pi^0$

$\rightarrow \; \pi^0 \rightarrow \gamma + \gamma$

Projection of Radiation



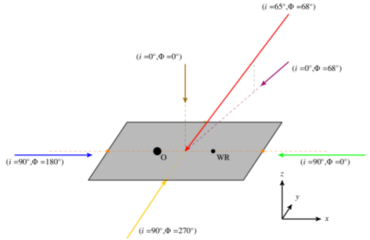
Properties of WR 11

- Electrons Suppressed:
  - High radiation fields
  - Strong magnetic field
- Dominant Process:

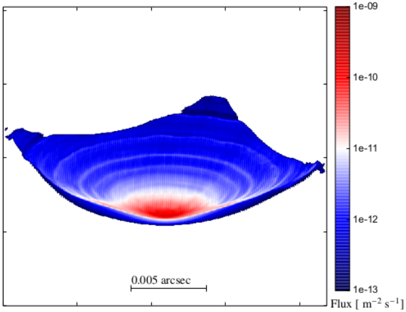
$\rightarrow \; p + p \rightarrow p + p + \pi^0$

$\rightarrow \; \pi^0 \rightarrow \gamma + \gamma$

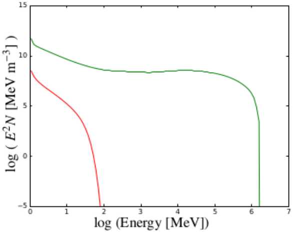
Projection of Radiation



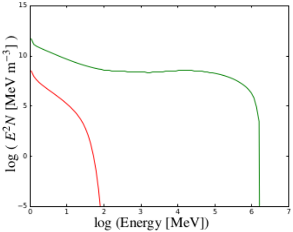
Pion-Decay Emission



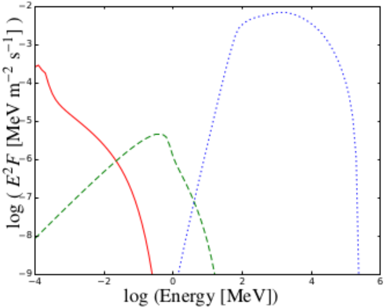
Integrated Particle Spectra



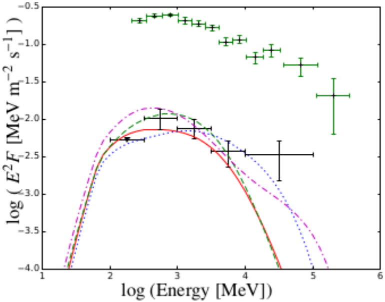
Integrated Particle Spectra



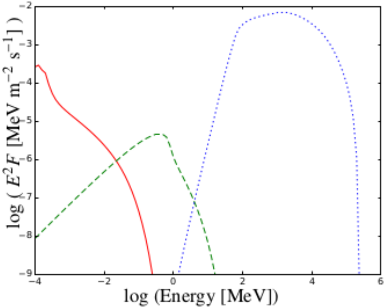
Non-Thermal Radiation



Comparison To Data

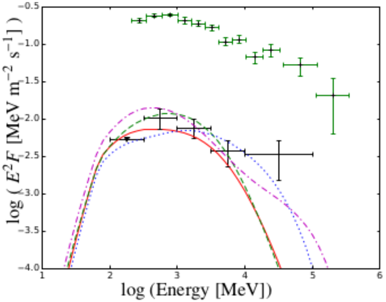


Non-Thermal Radiation

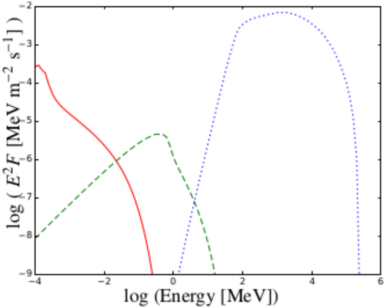


Gamma-Ray Emission II

Comparison To Data



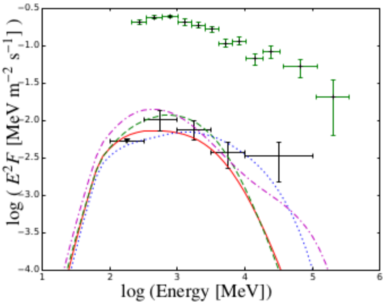
Non-Thermal Radiation



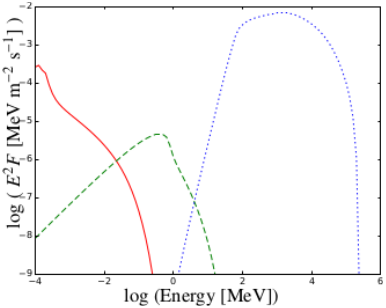
Conclusion

- WR 11: hadron accelerator
- Fit to data possible
- Max flux at apastron
- Min flux at periastron

Comparison To Data



Non-Thermal Radiation



Ongoing / Outlook

- Orbital Motion
- Other Systems
- New application: gamma-ray binaries