Wind accretion in Supergiant X-ray Binaries

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Geneva
February 2019
Introduction

The challenge of scales

1. clumps capture?
2. disc-like structure?

3 orders of magnitude

log length scale from compact accretor

NS rad. $R_{\text{NS}} \sim 15\text{kms}$
NS mag. rad. $\sim$ a few $100R_{\text{NS}}$

ext. acc. sphere $8R_{\text{acc}} \sim a/20$ to $a/2$

orb. sep. $a \sim 0.1\text{ AU}$

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Clumps in the wind

Accretion from a clumpy massive-star wind in SgXB, MNRAS 2018

IEM, Jon Sundqvist, Rony Keppens
Clump dimensions

Line-driven winds

Internal shocks

$\Rightarrow$ clumps

Pseudo-planar 2D simulations

$\rightarrow$ transverse extension resolved

3D simulation space embedded in the wind

O/B blue Supergiant
Structure of the flow and time variability of the mass accretion rate

Ballistic clumps

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Structure of the flow and time variability of the mass accretion rate

Bow shock @ accretion radius

- prevents direct accretion of clumps
- evacuation of angular momentum
Structure of the flow and time variability of the mass accretion rate

Bow shock @ accretion radius
- prevents direct accretion of clumps
- evacuation of angular momentum

Turbulent innermost shocked region
Structure of the flow and time variability of the mass accretion rate

- Bow shock @ accretion radius
  - prevents direct accretion of clumps
  - evacuation of angular momentum
  - instability @ NS magnetosphere required

**Mass flux (g·cm⁻²·s⁻¹)**
- 2.5E-4
- 1E-3
- 5E-3

**Mass density (g·cm⁻³)**
- 1E-13
- 1E-12
- 1E-11

**Turbulent innermost shocked region**

**Time-variability × 10**
Observations of Vela X-1

Phase ~ 0.25
- no tail in the L.O.S

Hardness enhanced
- not from source
- increase in $N_H$ (x7)
- 1h long

due to clump event?
- too small (1% of $R_{\text{star}}$)
- too packed
- too fast (~1,000km/s)

Grinberg et al. 2017
Orbital bending

Wind-capture discs in SgXB, A&A 2019

IEM, Andreas Sander, Jon Sundqvist, Rony Keppens
Slow VS fast winds: where should we draw the line?

3D ballistic wind (RK4)
Stellar parameters fixed

Roche potential +
radiative acceleration (w/ X-rays)

**Heavy Slow (HS)**

NS mass: $2.5M_\odot$
Normal acceleration
=> wind speed < orbital speed

**Light Fast (LF)**

NS mass: $1.5M_\odot$
Enhanced acceleration (50%)
=> wind speed > orbital speed

Similar mass inflow distribution

**BUT**

Net inflow of angular momentum non-zero for HS

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Wind-RLOF configuration

Density / 10^{-14} g·cm^{-3}

Velocity / km·s^{-1}

Light fast

Bow shock and Mach-1 misaligned
Sonic surface
Limited density enhancement
No disc
Wind-RLOF configuration

Bow shock and Mach-1 misaligned
Sonic surface
Limited density enhancement
No disc

Asymmetric shock
Orbital compression
High density enhancement
Spiral structure

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Wind-RLOF configuration

- Light fast
- Heavy Slow

- Density / 10^{-14} g·cm^{-3}
- Velocity / km·s^{-1}
- \( v_{\text{orb}} \)
- Temperature increase by factor \( x5,000 \)
- Asymmetric shock
- Orbital compression
- High density enhancement
- Spiral structure
- Limited density enhancement
- No disc
- Temperature increase by factor \( x5,000 \)
- Cooling required

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Cooling prescriptions and wind-capture disc

*Polytropic* prescription to reproduce cooling

- **Constant entropy**
- **Constant high temperature**
- **Constant low temperature**

- **Light fast**
- **Heavy Slow**

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Impact of clumps on time-variability

- *lower* than ballistic prediction
- cushioning *shock*
- limited absorption variability along LOS
- instabilities within a few $100 \ R_{\text{Schw}}$
- dependence on orbital separation (SFXT)

Orbital shearing and disc formation

- provided $v_{\text{wind}} < v_{\text{orb}}$
- ... and efficient cooling
- beyond NS magnetosphere

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### Perspectives

- the case of Cygnus X-1
- disc-like structure => disc wind? transient?
- NS (or BH) spinning-up

Merci!
Introduction

Mass transfer

Low-mass stellar companion

Permanent accretion disc
- multi-color black body
- support on top of which grows various instabilities

High-mass stellar companion
Intense radiatively driven **stellar winds**
- terminal velocity $\sim 1000$ km/s
- mass outflows $\sim 10^{-6} \, M_{\odot}/yr$

Low angular momentum flow $\Rightarrow$ disc? permanent?
Clumpy winds $\Rightarrow$ time variability?
1. Clumps in the wind of massive stars
   - mass and size
   - numerical setup
   - mass accretion rate
   - column density
   - observations of Vela X-1

2. Orbital bending of slow winds
   - slow VS fast winds
   - wind-RLOF configuration
   - cooling prescriptions
   - structure of the flow
   - angular momentum accretion rate

Transient discs
NS magnetosphere
Theory

Axisymm. BHL

Empirical mass acc. rate

\[ \frac{R_{\text{acc}}}{R_{\text{Schw}}} = \left( \frac{c}{v_{\infty}} \right)^2 \]

Axisymm. HD

Structure of the flow
Influence of the Mach #
Inner sonic surface

Relaxed 3D initial state

Inhomogeneous outer boundary conditions
Sheared inflow
Orbital effects

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Clump dimensions: 3D reconstruction

Stacking of a 2D time stripe... in both transverse directions... in both transverse directions...

Combined with arithmetic or geometric average

\[
S_{ijk} = \frac{S_{ij}}{S_{ik}}
\]

+ histogram correction

45 degrees rotation

Same stochastic properties

+/- z symmetry

Original signal retrieved on central slice

Spherical clumps
Numerical setup: stretched spherical mesh

$$\frac{R_{\text{out}}}{R_{\text{in}}} = 800$$

Radially stretched grid

Resolution

64 x 48 x 64

Axisymmetric flow

... How to resolve small-scale off-centered features?

\[ \rightarrow \text{AMR} \]
Numerical setup: selective AMR

Selective AMR
- inhibited at the poles (CFL cond.)
- inhibited in the wake of the accretor
- favored in the accretion cylinder

High effective resolution
- $512 \times 384 \times 512$
Column density: model

Local column density
- Time varying column density profile
- Dependence on inclination angle
- $N_H$ in every 3D direction at each time step

Orbital column density
- Phase dependent column density profile
- Dependence on inclination angle
- Isotropic or clumpy wind

$N_H$ vs. Orbital phase
- 0 (edge-on)
- Grazing
- $\pi/4$
- $\pi/2$ (face-on)
Mass accretion rate: activity diagram

Luminosity diagram: histogram of activity levels
- X-ray luminosity observed
- Numerical mass accretion rate

Role of orbital separation

Activity levels
- High levels cut off
- Main activity ~ 10%
- Max/min ~ 10 to 20
Absorption => enrichment of low-level activity

High luminosity flares unexplained by clumps alone
Angular momentum accretion rate

NS spin period in Vela X-1 ~ 283s

=> characteristic spin-up time as low as ~ 10 kyrs

N.B.: high mass accretion rate