3D relativistic hydro models for SS433: virtual views on precessing jets

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Outline

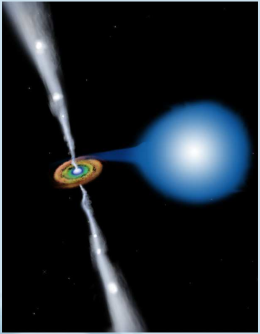
Team

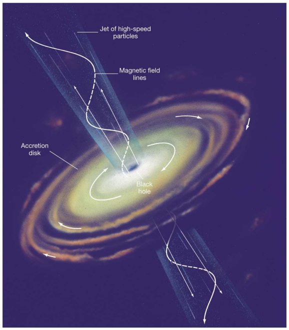
- Monceau-Baroux Remi - Phd student at CmPA, KU Leuven
- Keppens Rony - Doctor at CmPA, KU Leuven - Supervisor
- Meliani Zakaria - Doctor at Luth, OBsPM - SRHD simulation of relativistic jet
- Porth Oliver - Doctor at CmPA, KU Leuven / Department of Applied Mathematics, The University of Leeds - Radio mapping

The presence of relativistic jets in the universe

- AGN jets: FR-I, FR-II, etc: Expected to play an important role in the reheating of galaxy clusters. Ex: M87
  The effect of angular opening on the dynamics of relativistic hydro jets - [Monceau-Baroux et al. 2012]
- X-ray binary jets. Ex: SS433
  The effect of the Lorentz factor on the model of SS433 - [Monceau-Baroux et al. 2014 - DOI:10.1051/0004-6361/201322682]

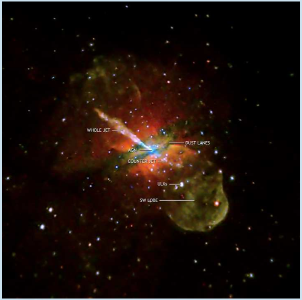
False twins

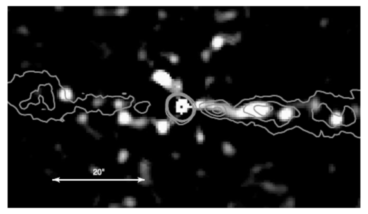


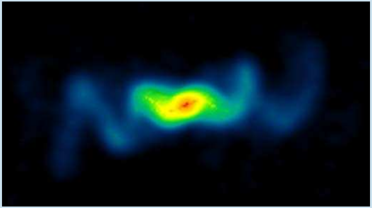


- The accretion disk of a compact object (neutron star / black hole) releases matter in the form of winds. Many studies are made to explain how a jet can arise from these winds (see [Blandford & Payne 1982][Bogovalov and Tsinganos 2004])

Jets in the sky with diamants







Left top: Chandra X-ray Image of Centaurus A (Credit: NASA/CXC/CfA/R.Kraft et al.); Left bottom: 0.3 to 5.0 keV CHANDRA image of NGC 4261 (3C 270) after subtracting the diffuse component. The contours correspond to radio emission from a 4.9 GHz VLA observation (Zezas et al 2005); Right: VLA observations of SS433

To study or not study jets, why is it our question?

Aims for the study of X-ray binary associated jets:

1. Better understandings of relativistic jets:
   1. How does the precession of the jet affect the jet/medium interactions
   2. How do the properties of the jet (velocity/density ratio) affect the jet/medium interactions.
2. Comparison to observations, in case of SS433 with the VLA telescope. Need the ability to do radio mapping.

Outline

How do we do that?

Framework

1. Relativistic version of hydrodynamical equations
2. Synge gas equation of state
3. Code used for the simulations: MPI-AMRVAC (https://gitorious.org/amrvac/)
4. Adaptive Mesh Refinement and Message Passing Interface

Where is Charly?

Problem?

What question should you ask yourself about that model?

Wait a minute!

Where is $\vec{B}$?

Charly is not important...

Pro

Why $\vec{B}$ shall be here: radio/X emissions = synchrotron

Con

Far away from the source: kinetic mechanisms should dominate magnetic ones. Actual measure of a few mG

For later on

Pressure taken as a proxy for magnetic field for radio emission.

What we know ...

Our input parameters are coming from observation:

1. The thermodynamic conditions of the ISM, pressure and density: P_{ISM}, ρ_{ISM} (Safi-Harb Oegelman 1997),
2. The energy flux of the jet, L_j (Brinkmann et al 2005),
3. The jet opening angle and the jet angle to its precession axis: α_j, θ_{prec} (Margon et al. 1979),
4. The velocity of the jet head: v_{head} (Roberts et al 2008).

... and what we do not!

We fix

1. The jet Lorentz factor, γ_j,
2. $P_j = P_{ISM}$,

We need

1. The jet density, ρ_j.

Playing with known parameters

As for Meliani et al 2008 and Monceau et al 2012, we compute the integrated energy flux over the beam cross section as:

$$L_j = (\gamma_j h_j - 1)\rho_j \gamma_j \pi R_j^2 v_j, \tag{1}$$

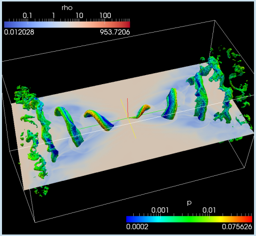
where ρ_j, R_j, v_j are the jet density, radius and velocity.
$\rho_j h_j = \rho_j + \frac{\Gamma}{\Gamma - 1} P_j$ is the enthalpy.
We can then obtain ρ_j.

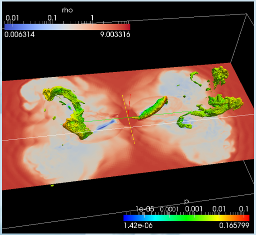
4 cases for a global picture

Case	γ_b (v_b)	η	$\theta_{\rm prec}$
A	1.036 (0.26c)	28.6	20°
B	1.87 (0.845c)	0.8	20°
C	1.036 (0.26c)	28.6	10°
D	1.87 (0.845c)	0.8	0°

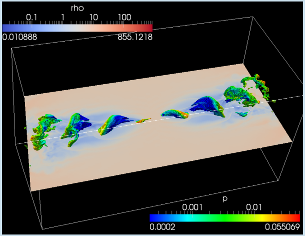
Table : Parameters for the simulations. With $\eta = \gamma_j^2 \frac{\rho_j h_j}{\rho_{ISM} h_{ISM}}$ the inertia ratio.

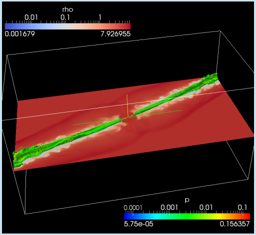
Let's have a look





Top: case A, $\gamma = 1.036$ and $t = 2$,
Bottom: case B, $\gamma = 1.87$ and $t = 2$,

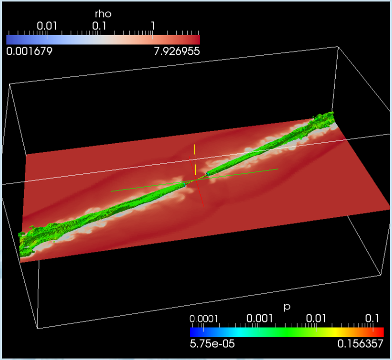




Top: case C, $\gamma = 1.036$ and $t = 2$,
Bottom: case D,$\gamma = 1.87$ and $t = 0.5$.

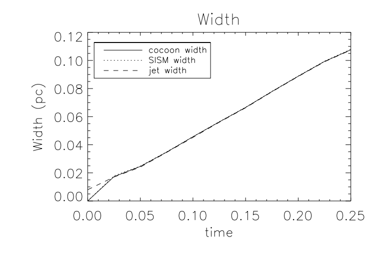
Outline

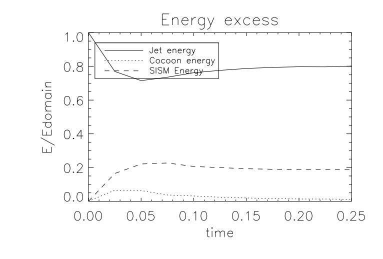
Case D - Overview

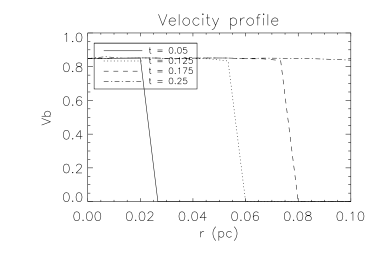


1. 'classic' static case
2. $\gamma = 1.87$, mildly relativistic
3. Bullet like propagation, canonical relativistic jet behavior

Case D - Dynamics

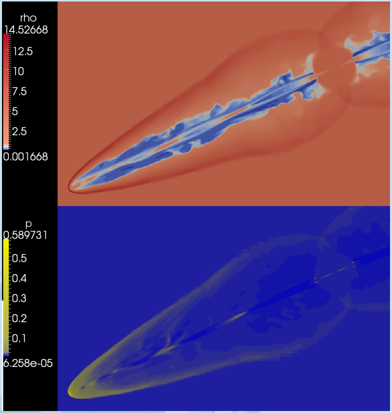


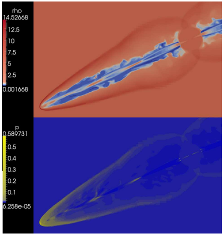




1. Path set by the jet head
2. It propagates with
   $v_j^{marti} = \frac{\sqrt{\eta}}{\sqrt{\eta}+1} v_{beam}$ with
   $\eta = \gamma_j^2 \frac{\rho_j h_j}{\rho_{ISM} h_{ISM}}$
3. 'Near' flat velocity profile: only interaction at the head
4. Most energy in the jet beam: low interaction with the medium

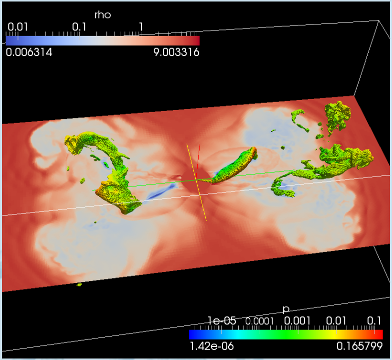
Case D - internal structure





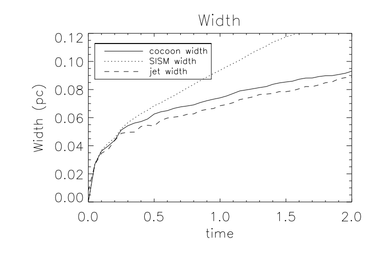
1. Recollimation shocks
2. Structured beam
3. Instabilities advected

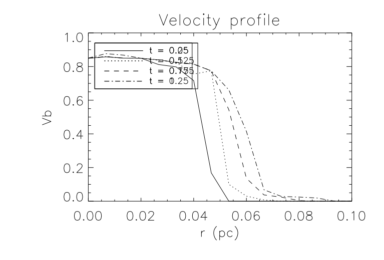
Case B - Overview

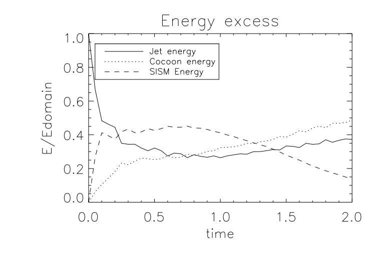


1. Precessing jet
2. Mildly relativistic
3. $\gamma = 1.87,\ \theta = 20^{\circ}$

Case B - Dynamics

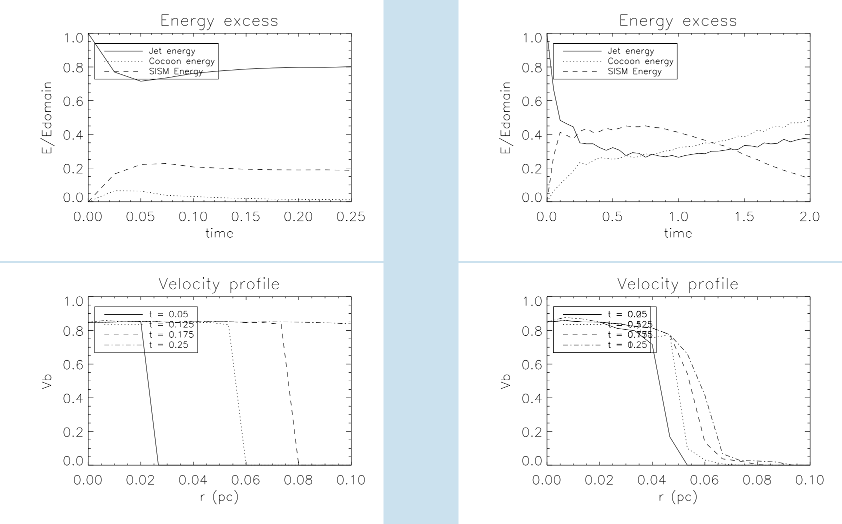




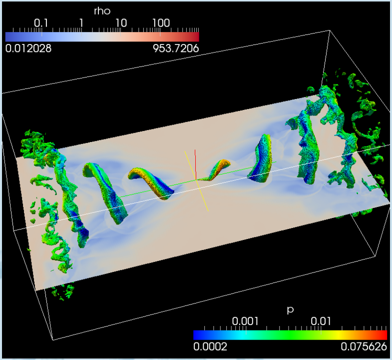


1. Deceleration of the jet head velocity to an asymptotic regime
2. Sub-sonic velocity of the jet head
3. Continuous deceleration along the path of the beam
4. Knee and ankle of the velocity profile
5. 30% energy transferred to cocoon and 40% to the SISM

Effect of precession - case B and D

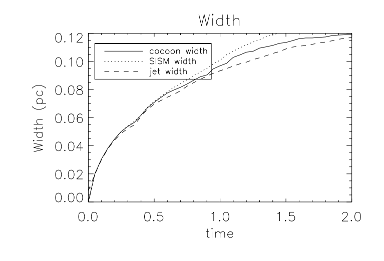


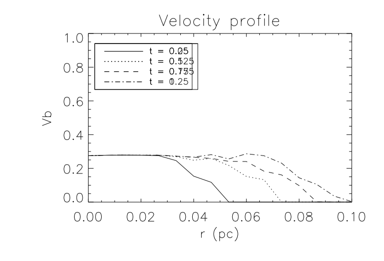
Case A - Overview

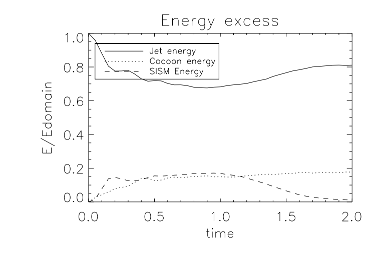


1. Canonical SS433 'kinematic model'
2. Barely relativistic
3. $\gamma = 1.036,\ \theta = 20^{\circ}$

Case A - Dynamics

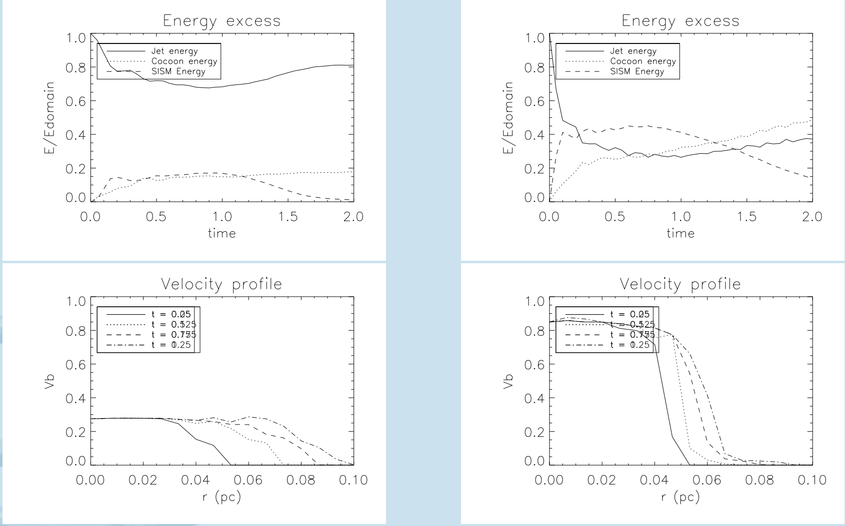






1. Deceleration of the jet head velocity
2. Sub-sonic velocity of the jet head
3. Continuous deceleration along the path of the beam
4. 40% energy transferred to cocoon and SISM (20% each)

Effect of Lorentz factor - case A and B



Conclusion on dynamics

1. Case D shows the formation of a structured beam and inner standing shocks known from the study of relativistic jets. It interacts weakly with the medium.
2. Precessing case where a shock propagates in front of the jet head display a knee and ankle velocity profile showing how the SISM is heated and accelerated by the shocks.
3. The precession increases the surface of interaction and the energy transfer
4. Increased Lorentz factor slows down the expansion of the interaction region. As the inertia ratio increases drastically with the Lorentz factor we observe the expected higher interaction with the medium.

Outline

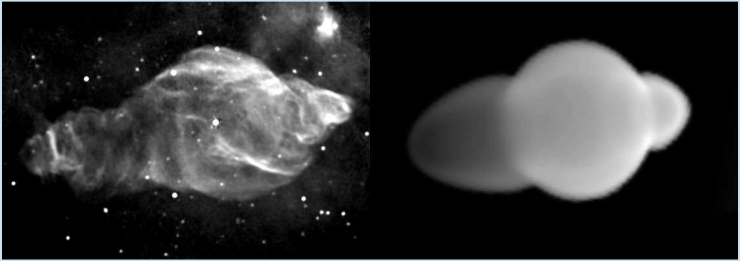
Radio Mapping

- Script for radio mapping by Oliver Porth (Porth 2014, DOI:10.1093/mnras/stt2176)
- We follow the evolution of the energy spectrum of the electrons: $f(\epsilon) = A\epsilon^{-\Gamma}$ for $\epsilon \leq \epsilon_\infty$, with $\Gamma = 0.6$.
- We use the emission equation from Camus et al (2009).

$$I = n_0 D^2 B_\perp (\frac{\rho_{e0}}{\rho_e})^{-\frac{\Gamma+2}{3}} \epsilon^{1-\Gamma} (1 - \frac{\epsilon}{\epsilon_\infty})^{\Gamma-2}, \tag{2}$$

  where e and m are the electron charge and mass, ρ_e and ρ_{e0} are the electron density and initial density, ϵ_∞ the electron cut off energy, $\nu = c_1 B_\perp \epsilon^2$, $c_1 = 3e/4\pi m^3 c^5$, $B_\perp$ is the component of the magnetic field normal to the line of sight in the fluid frame and $D = \nu_{obs}/\nu$ is the Doppler factor.
- B taken equal in intensity to $\sqrt(P)$
- Thin medium
- Ray tracing

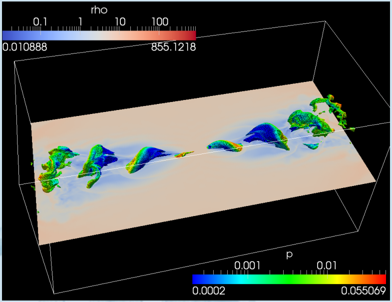
Zavalas simulation of SS433



Comparison of the radio-continuum image with the simulated column electronic density map of model M4. The left-hand panel shows the 1415-MHz image in grey-scale and contours of the W50 SNR, obtained with the VLA by Dubner et al. (1998), in equatorial coordinates (north is up). The right-hand panel shows the simulated map in a grey colour scale. A distance of 3 kpc to SS433 was assumed. (Zavala 2008)

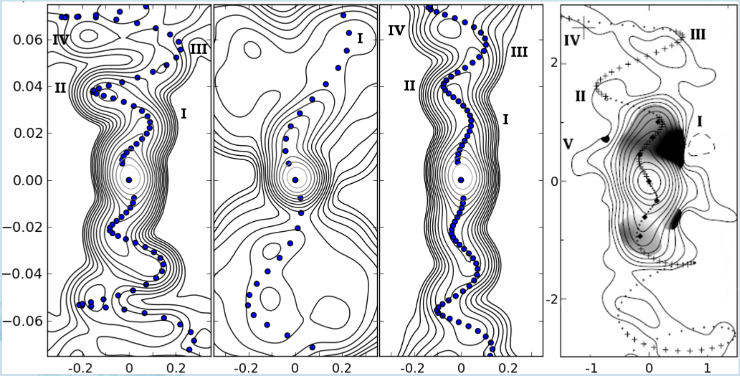
Need 10° precessing angle to reproduce the image at 20pc

Case C - Overview



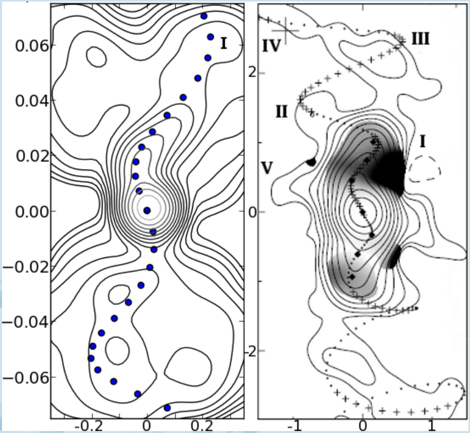
1. Barely relativistic
2. $\gamma = 1.036,\ \theta = 10^\circ$

Radio mapping - Overview



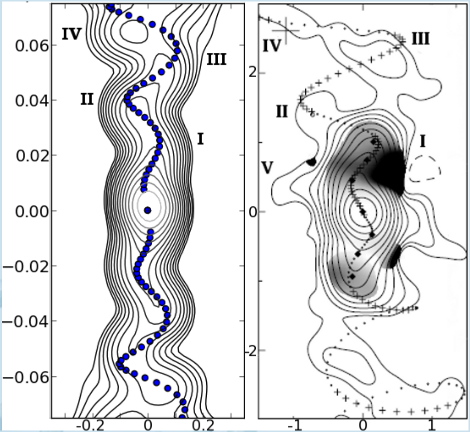
Left to right: Radio map from simulations Case A, Case B and case C. Units are in parsec, object is estimated to be at a distance of 5.5 kpc. All graphs overplot the kinematic model with parameters corresponding to the case. Right: VLA image of the microquasar SS433 in the constellation Aquila, adapted from Roberts et al. 2008, units are in arcsecond.

Case B - Too far



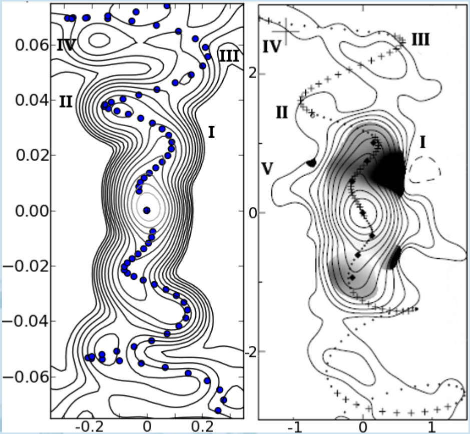
1. Radio elements too far from the source
2. Strong beaming effect

Case C - Too narrow



1. Radio elements too close to the precession axis.
2. Different precessing angle with time?

Case A - Good fit



1. Similar appearance
2. The kinematic model underestimates interactions on both simulations and observations.
3. Absence of the radio ruff

Conclusion on dynamics

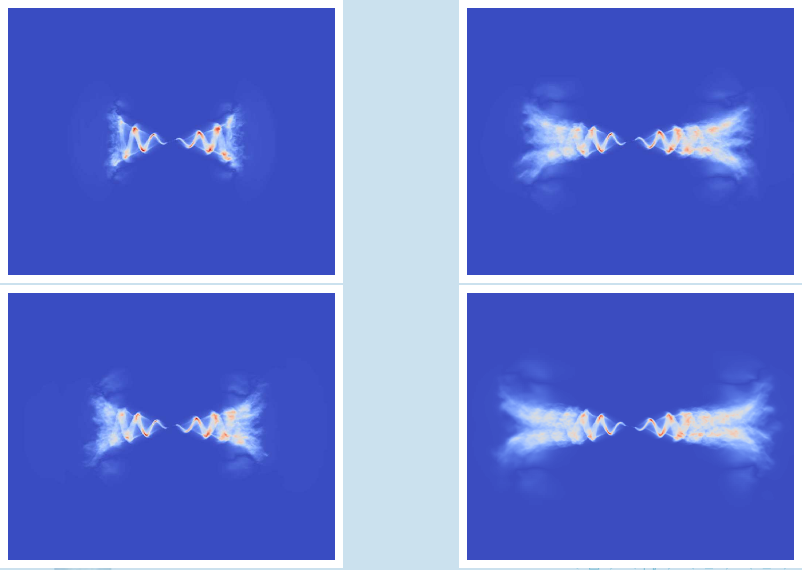
1. Discrepancy at sub parsec scale and 20 parsec: time variation of the precessing angle? Recollimation?
2. Validation of the kinematic model for SS433. Only case A opening angle and Lorentz factor gets a similar picture to VLA observation.
3. The kinematic model needs to be corrected for interactions. It overestimates both simulations and observations.
4. Absence of the radio ruff: are they coming from the disk wind?

Wait a minute!

We have a problem:

1. Small scale (under parsec): 20°
2. Large scale (over 30 parsec): 10°

Spatial Evolution



Acknowledgement

Special thanks to Rony Keppens, Zakaria Meliani
and Oliver Porth
Dank u wel

Outline

Equations of Relativistic Hydrodynamics

Equations of Relativistic Hydrodynamics

1. Continuity Equation

$$\frac{\partial \rho\gamma}{\partial t} + \vec{\nabla} \cdot \rho\gamma\vec{v} = 0 \qquad (3)$$

2. Momentum Equation

$$\frac{\partial \vec{S}}{\partial t} + \vec{\nabla} \cdot (\vec{S}\vec{v}) + \vec{\nabla} p = 0 \qquad (4)$$

3. Energy Equation

$$\frac{\partial \tau}{\partial t} + c^2\vec{\nabla} \cdot (\vec{S} - \rho\gamma\vec{v}) = 0 \qquad (5)$$

1. Momentum Density

$$\vec{S} = \frac{h}{c^2}\gamma^2\rho\vec{v} \qquad (6)$$

2. Specific Enthalpy

$$h = c^2 + \epsilon + \frac{p}{\rho} \qquad (7)$$

3. Energy Density

$$\tau = \rho h\gamma^2 - p - \rho\gamma c^2 \qquad (8)$$

Closure equation - The synge gas equation of state

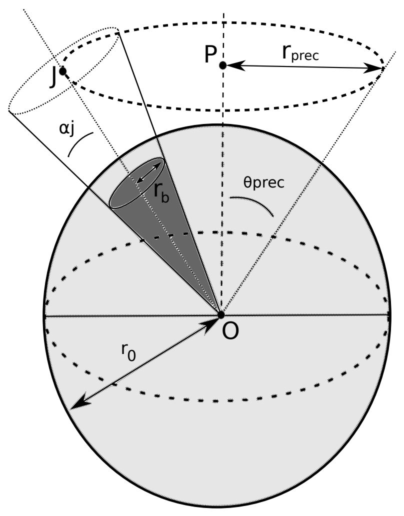
1. Mathews approximation to the Synge gas equation

$$p = (\frac{\Gamma - 1}{2})\rho(\frac{e}{m_p} - \frac{m_p}{e}) \tag{9}$$

2. Which gives a local effective polytropic index

$$\Gamma_{eff} = \Gamma - \frac{\Gamma - 1}{2}(1 - \frac{m_p^2}{e^2}) \tag{10}$$

Geometry



1. Binary system is not visible
2. Precession with 162 days
3. Overwrite central region
4. Double jet