THE COMPLEX MORPHOLOGY OF THE X-RAY AND OPTICAL EMISSION FROM HH 154: THE PULSED JET SCENARIO

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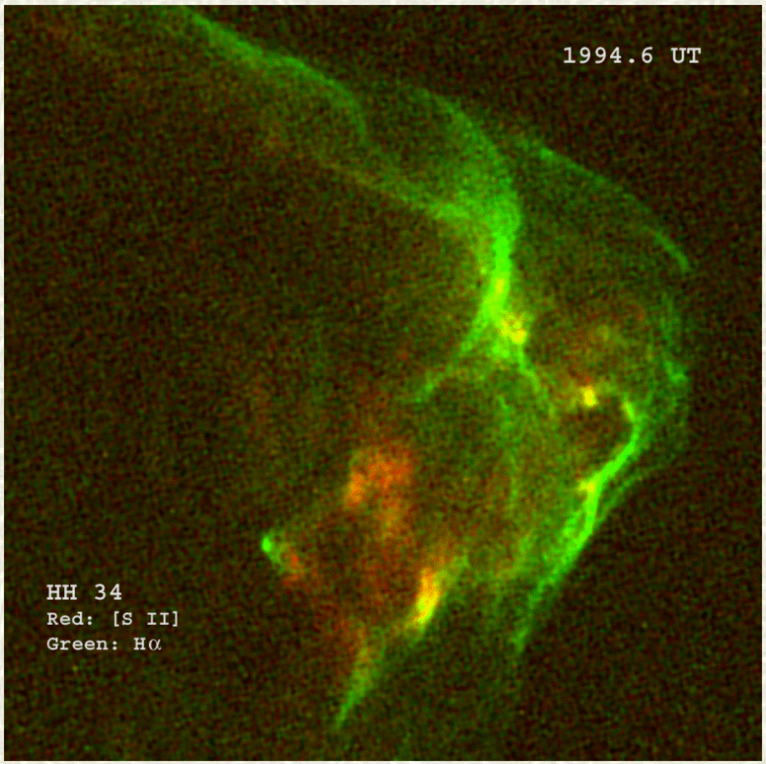
Outline

- First observations of the X-ray emission from protostellar jets
- First hydrodynamic model and synthesis of the X-ray emission from protostellar jets
- 2005 X-ray and optical observations of the emission from HH 154
- Modeling X-ray emission from a pulsed jet

Herbig - Haro (HH) objects

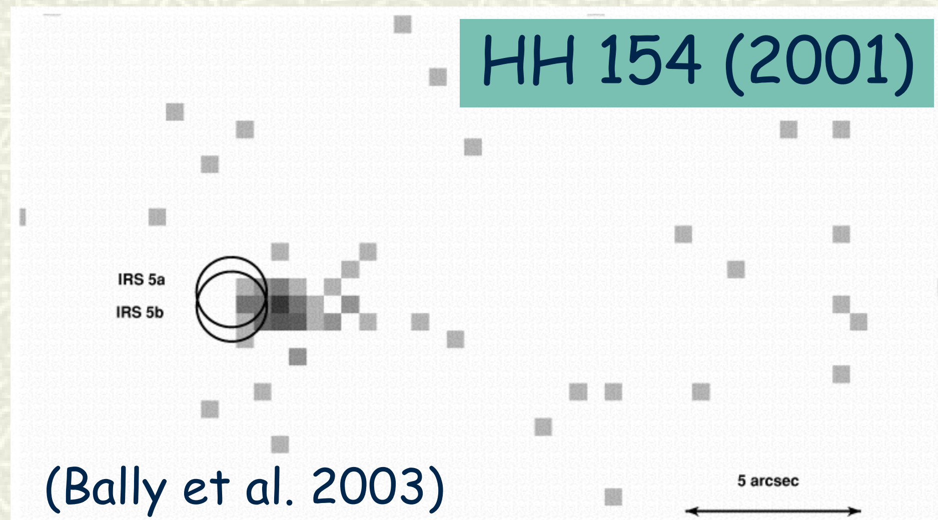
- HH objects: shocks formed at the interaction front between a supersonic jet and the surrounding medium



(Hartigan)

$$T_{\rm psh} = \frac{\gamma - 1}{(\gamma + 1)^2} \left(\frac{m v_{\rm sh}^2}{k_{\rm B}} \right)$$

X-ray emission
discovered from HH objects
for a total of 6 since 2000:
the first 2 (in 2000):



(Bally et al. 2003)

Close up view with Chandra ACIS-I

- Pravdo et al. (2001)
- Raga et al. (2002): analytic model

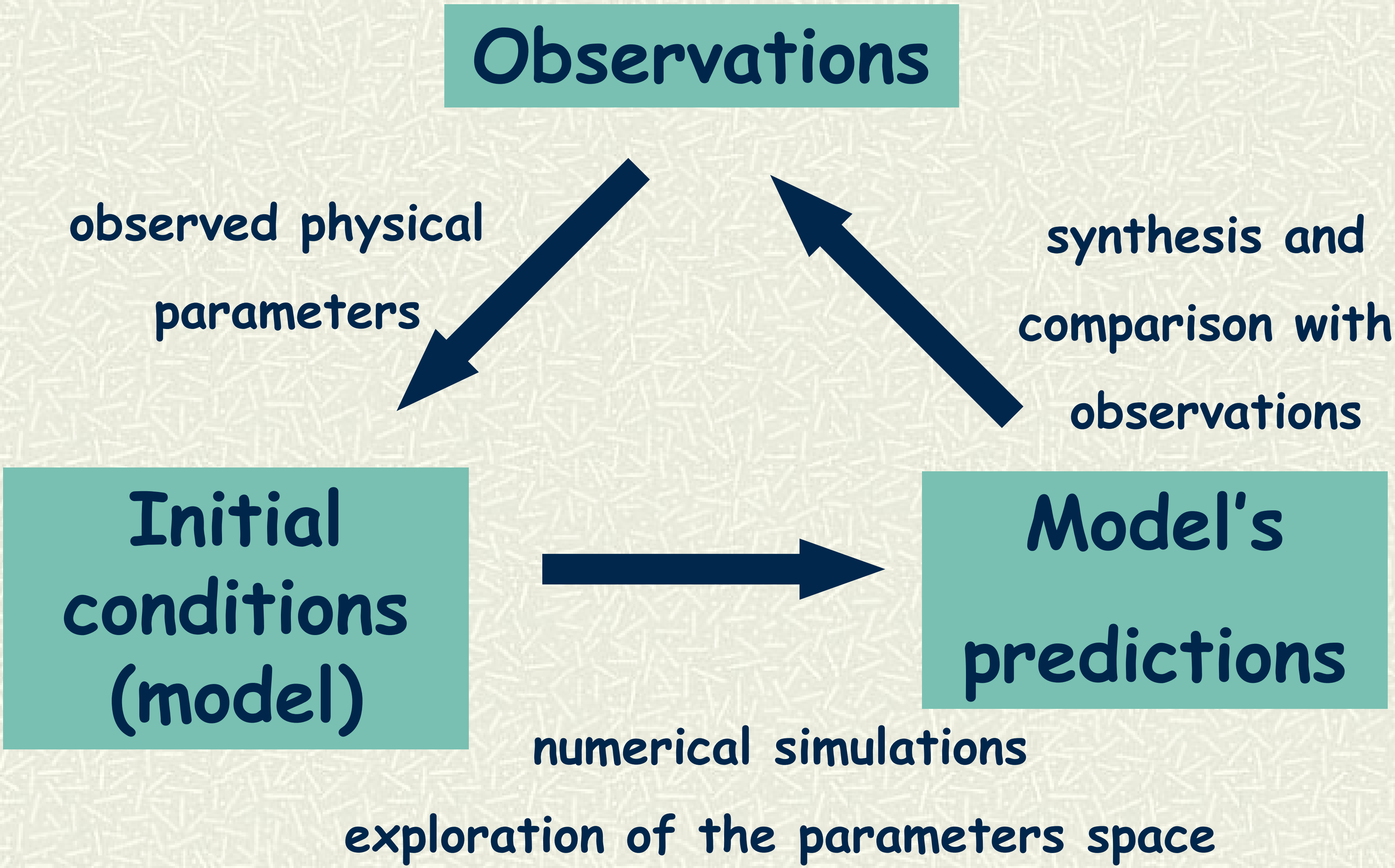
X-ray emitting protostellar jets

- Observed with both XMM and Chandra: 2000, 2001, 2005
- Strongly absorbed stellar corona: A_V (star/jet)= (150/ 7) mag
- The nearest most luminous jet: > 60 cnts in ~ 100 ks (single exposure)

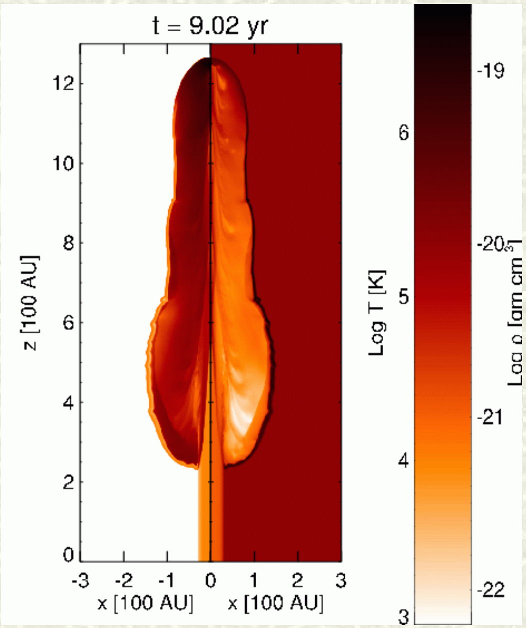
object	L_X [10^{29} erg s^{-1}]	T [MK]	N_H [10^{22} cm^{-2}]	d [pc]	References
HH 2	5.2	2.7	< 0.09	480	Pravdo et al. (2001)
HH 154	3.0	2.0-7.0	1.40	140	Favata et al. (2002)(2006) Bally et al. (2003)
HH 80/81	450	1.5	0.44	1700	Pravdo et al. (2004)
HH 168	1.1	5.8	0.40	730	Pravdo & Tsuboi (2005)
HH 210	10	0.8-3.8	0.80	450	Grosso et al. (2006)
DG Tau	0.12	3.4	0.3	140	Guedel et al. (2008)

Bonito et al. (2007)

Method


Observations
observed physical parameters
synthesis and comparison with observations
Initial conditions (model)
Model's predictions
numerical simulations
exploration of the parameters space

Spectral synthesis (1)



axial symmetry

Bonito et al. (2004, 2007)

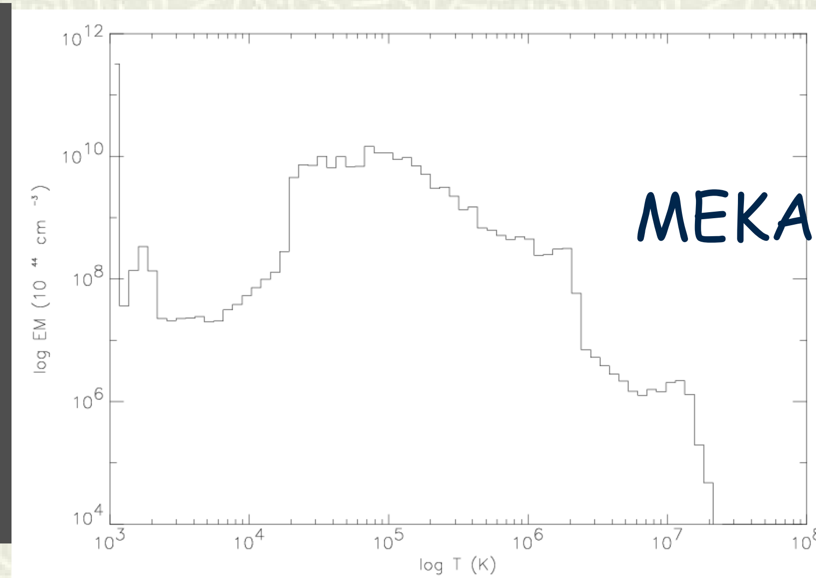
$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0\,, \qquad \frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \rho \mathbf{v}\mathbf{v} + \nabla P = 0$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho E + P)\mathbf{v} = -\nabla \cdot q - n_e n_H \Lambda(T)$$

$$E = \epsilon + \frac{1}{2}|\mathbf{v}|^2\,, \qquad P = (\gamma - 1)\rho\epsilon\,,$$

$$q_{spitzer} = -k_s T^{5/2}\,\nabla T$$

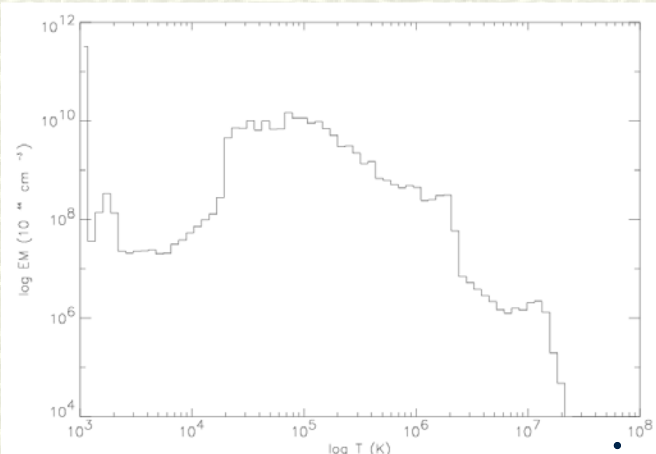
$$q = \left(\frac{1}{q_{spitzer}} + \frac{1}{q_{sat}}\right)^{-1}, \qquad q_{sat} = -\mathrm{sign}(\nabla T)\; 5\phi\rho c_s^3$$



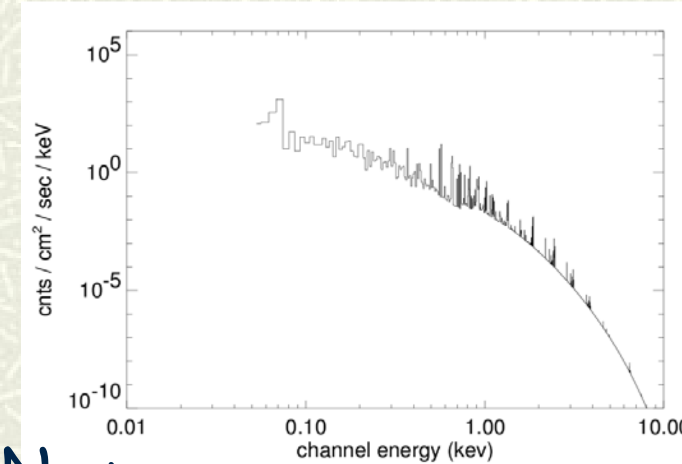
MEKAL code

FLASH (Fryxell et al.2000)

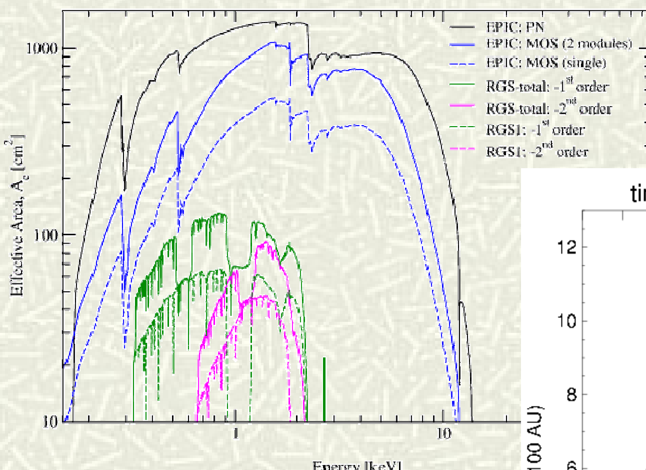
Spectral synthesis (2)

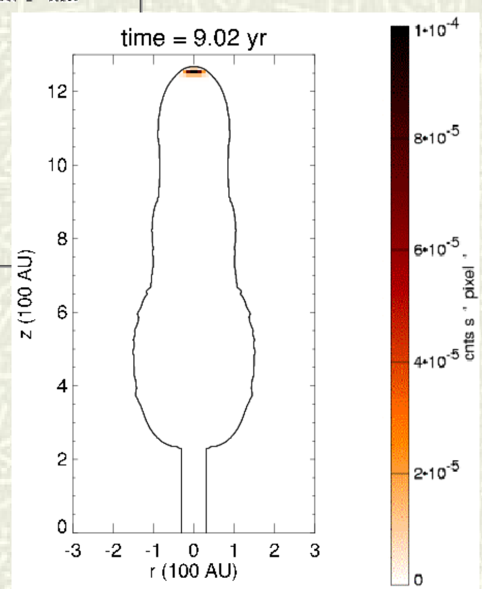


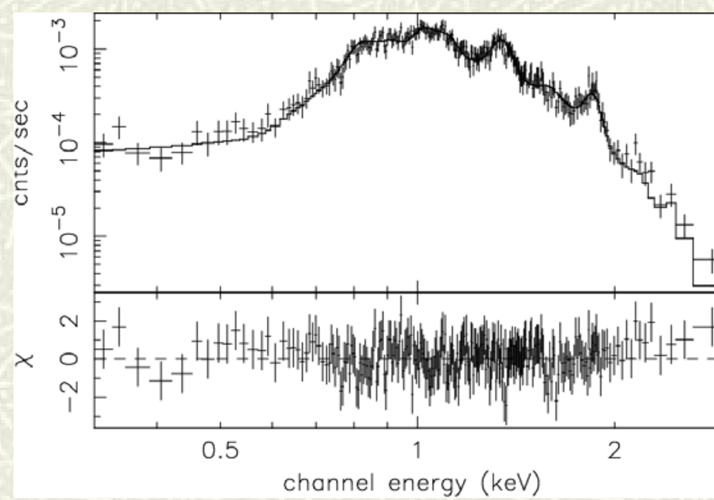
MEKAL code



instrum. resp. + N_H +
Poisson statistics



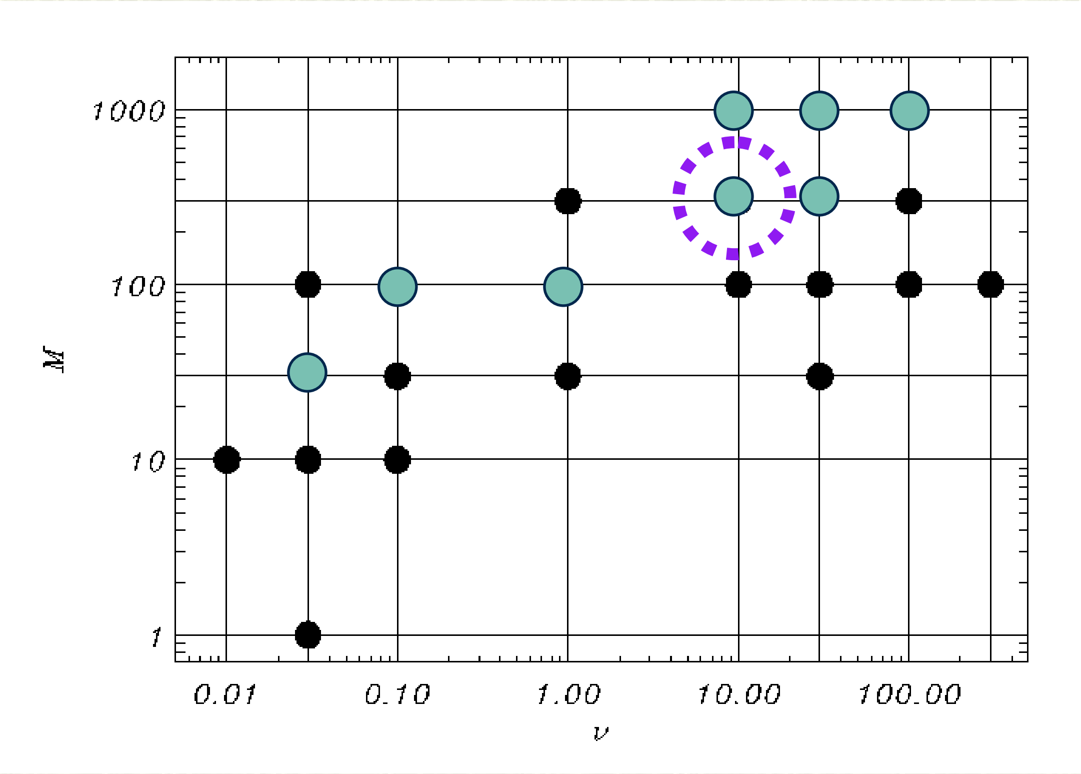




Bonito et al.

(2004, 2007)

Exploration of the parameters space: continuous jet model



varying n_j,

initial density of the jet

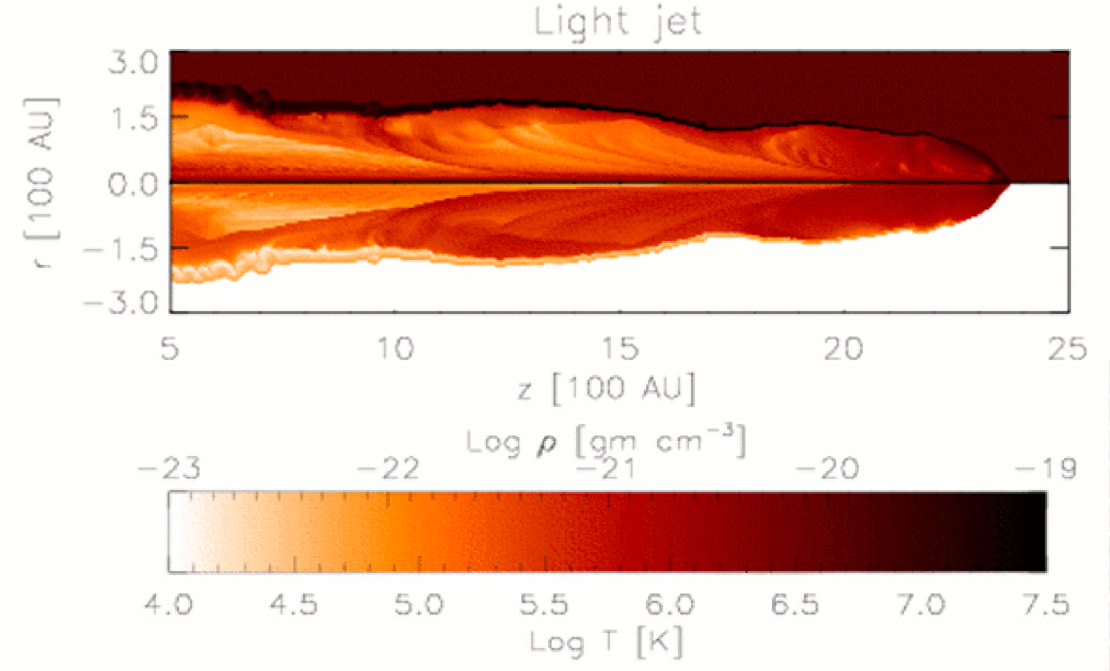
varying r_j ,

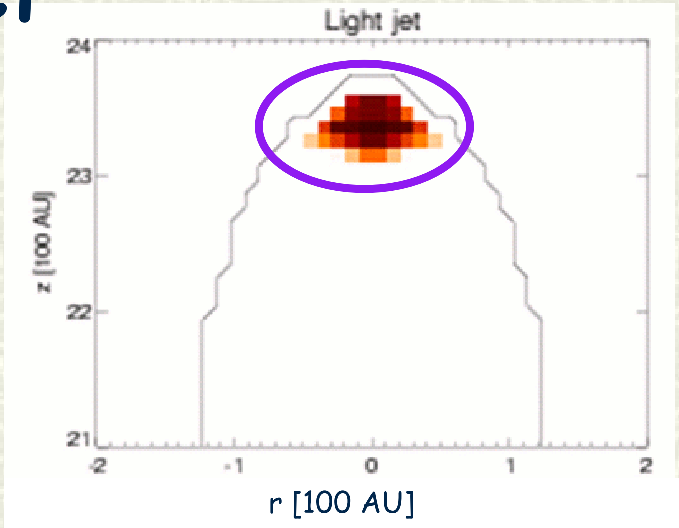
initial radius of the jet

- $M = v_j/c_a$ = Mach number
- $\nu = n_a/n_j$ = density ratio

Bonito et al. (2007)

Continuous jet model





Predicts detectable

proper motion (500 km/s)

blob X = point-like

due to the strong N_H

proved

by our model:

first X-ray synthesis from

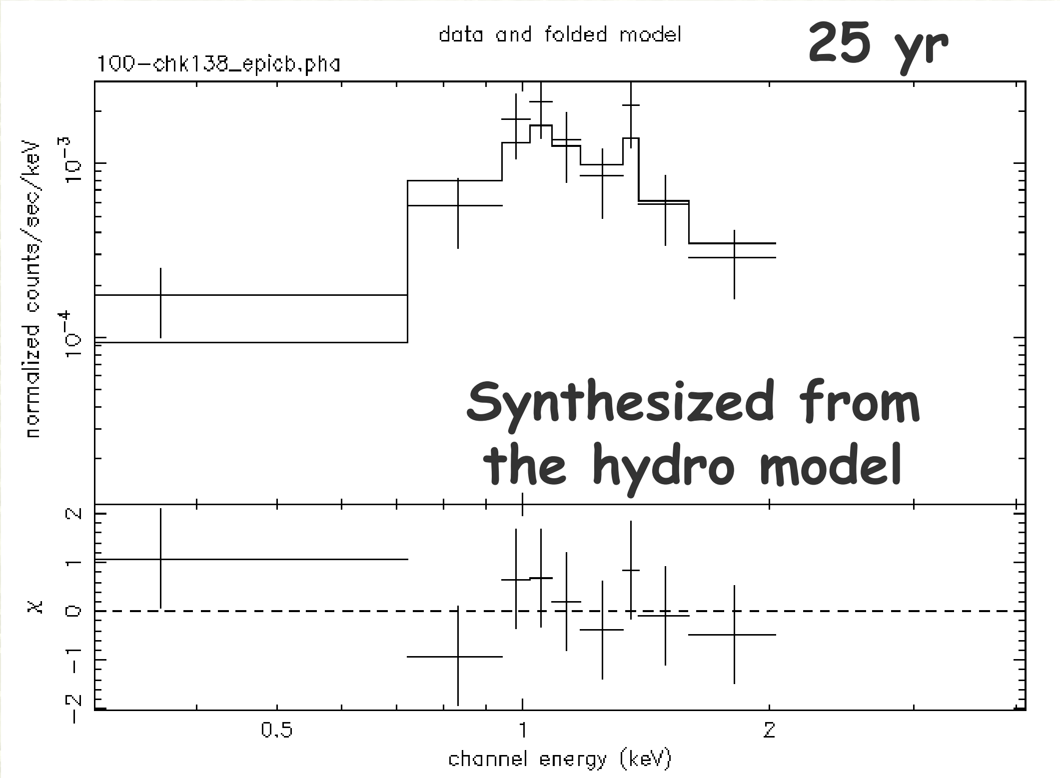
protostellar jets

model	ν	M	v_j [km s^{-1}]	n_a [cm^{-3}]	T_a [10^4 K]
light	10	300	1400	5000	0.1

Bonito et al. (2004; 2007)

X-ray emission from a light jet

(XMM-Newton/EPIC-pn)




```
Model:  wabs<1>( mekal<2> )
Model Fit Model Component  Parameter  Unit     Value
par   par  comp
  1     1    1   wabs        nH        10^22     1.51914     +/-   0.319504
  2     2    2   mekal       kT        keV      0.293114     +/-   0.103573
  7     7    2   mekal       norm              7.151831E-05 +/-   0.239805E-03
---------------------------------------------------------------------------
---------------------------------------------------------------------------
Chi-Squared =        4.004274     using     9 PHA bins.
Reduced chi-squared =      0.6673790     for      6 degrees of freedom
Null hypothesis probability = 0.676
```

Model (Bonito et al. 2004):

count rate = 1.2 cnts/ks

T = $(3.4 \pm 1.2)\times10^{6}$ K

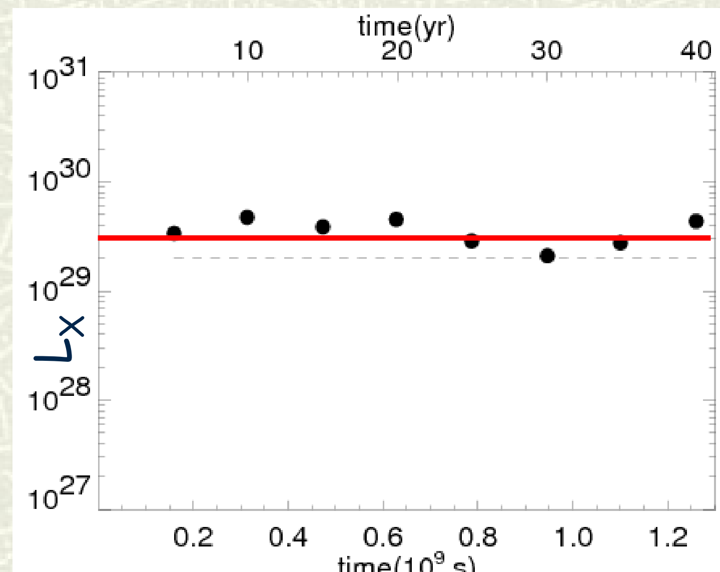
Fx = 1.4×10^{-13} erg/cm^2/s

Observations (Favata et al. 2002):

count rate = 1.0 cnts/ks

T = $(4.0 \pm 2.5)\times10^{6}$ K

Fx = 1.3×10^{-13} erg/cm^2/s



X-ray emission from a light jet
(XMM-Newton/EPIC-pn)

Shocks from supersonic jets: reproduce in a natural way the observed L_X and $T_{best\text{-}fit}$

prediction: $v_{sh} \sim 500$ km/s

Natural candidate to explain the physical mechanism of the X-ray emission from protostellar jets

Model (Bonito et al. 2004):
count rate = 1.2 cnts/ks
$T = (3.4 \pm 1.2) \times 10^6$ K
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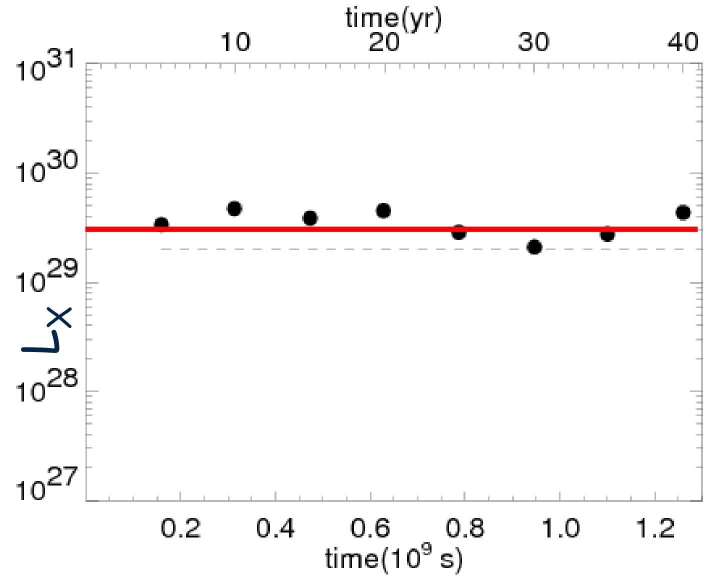
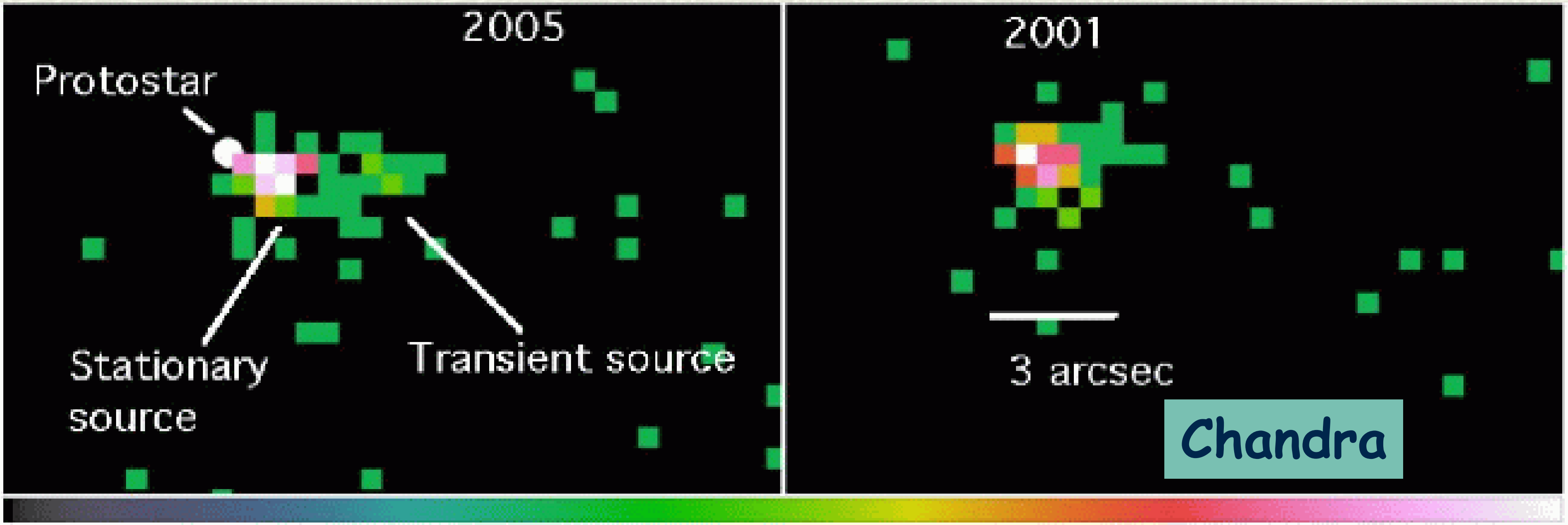


Morphological evolution in X-rays



- Complex morphology: two components

1) point-like, stationary (over 4 yr)
2) elongated

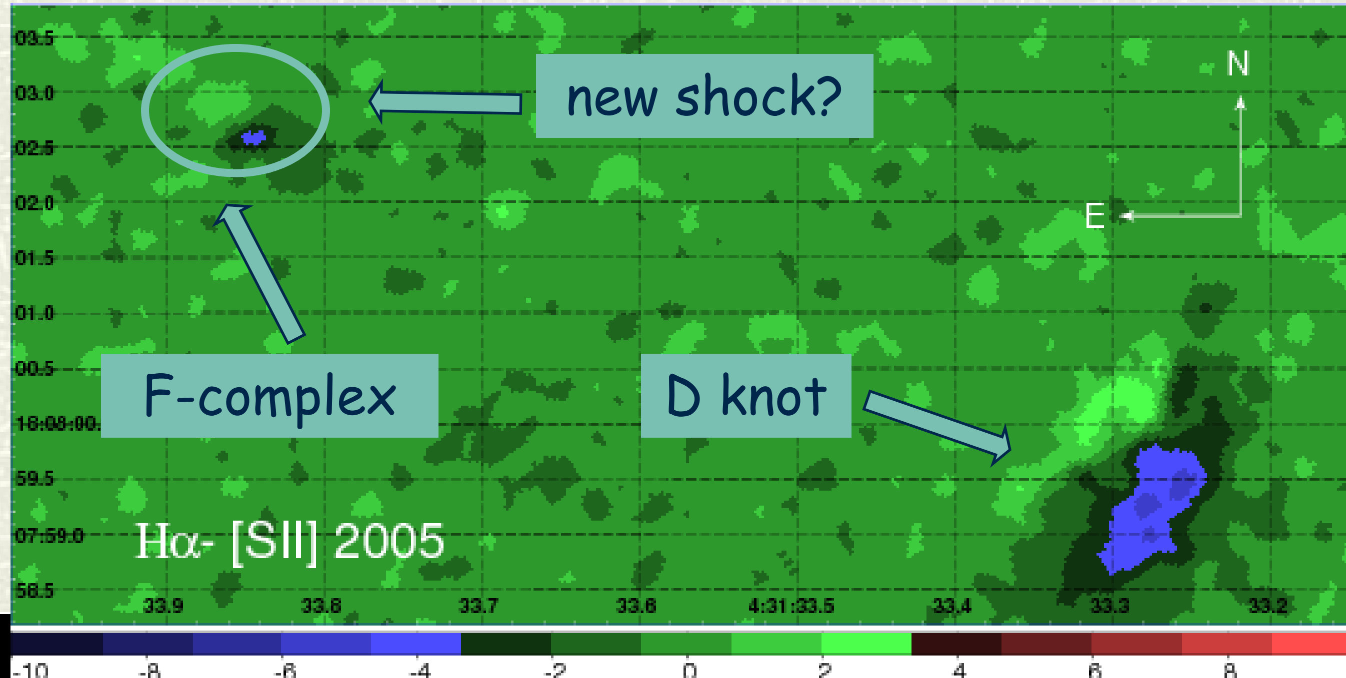
- Lengthening of X-ray source (component 2) consistent with proper motion predicted by the model detected for the first (and only) time
- Speed consistent with model's results: 460 km/s

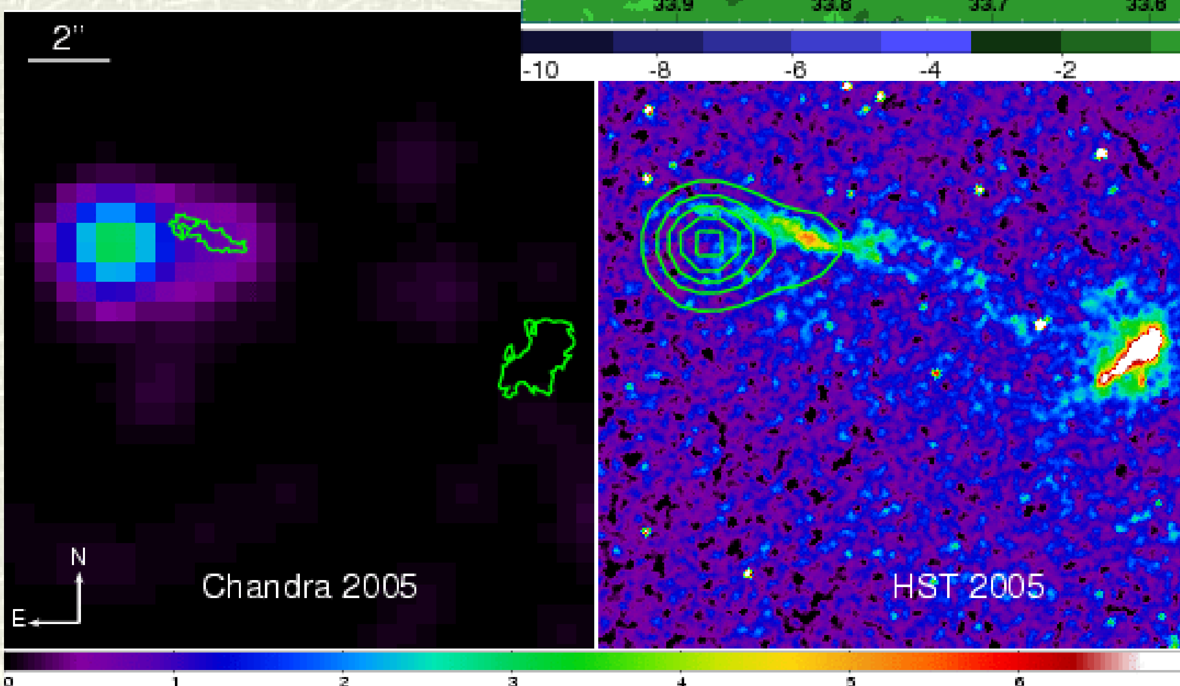
to verify the model

Favata, Bonito, Micela, Fridlund, Orlando, Sciortino, Peres (2006)

X-ray vs. optical emission

Bonito et al. (2008)





- X-ray emission from the base of the optical jet
- Complex morphology
- Variability:
  t ~ few years

⬇

single exposure

Open questions

First model: does not explain some observed features

⬇

(Guedel's talk)

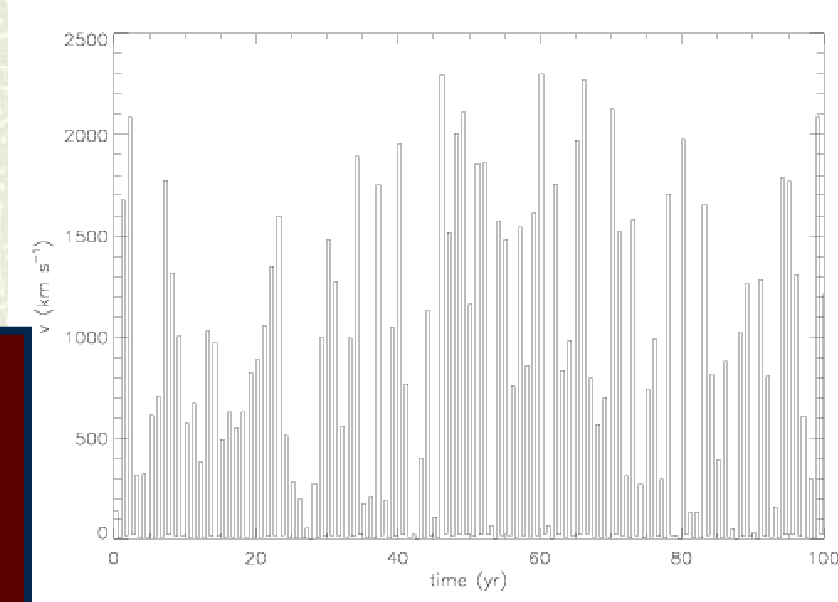
New model to explain:

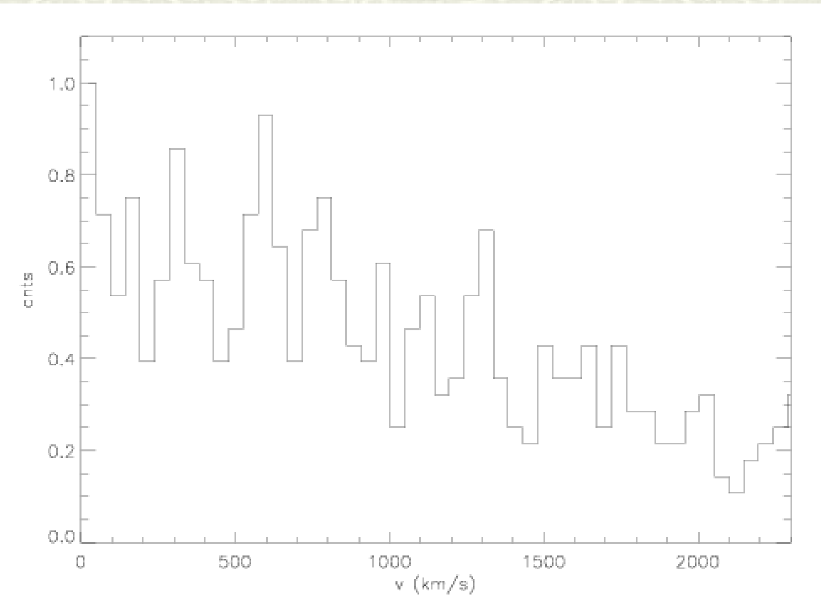
- X-ray emission from the base of the jet (HH 154, DG Tau)
- Complex morphology (the first and only case = HH 154)
- Variability (the first and only case = HH 154)

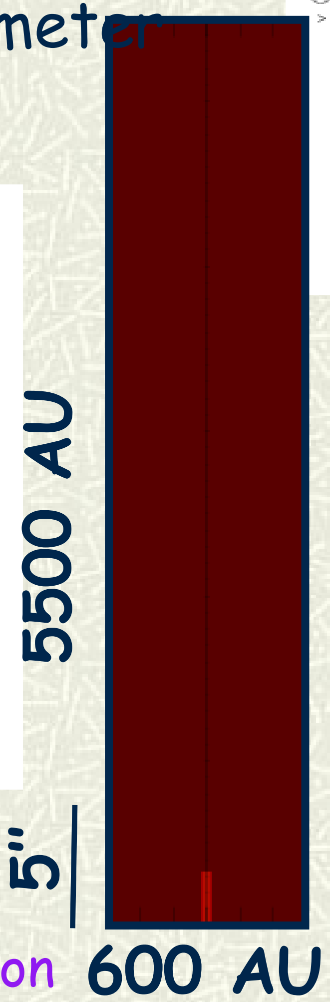
common feature for X-ray emitting HH jets

The pulsed jet scenario

- Basic physics = continuous jet
- "New" model: v(t)
  (previously used for optical knots;
  related to episodic accretion phoenomena)
- Exploration of the parameter space: M, ν, n_j, v(t), ...







- Few blobs at high speed
- Most of the blobs at low speed

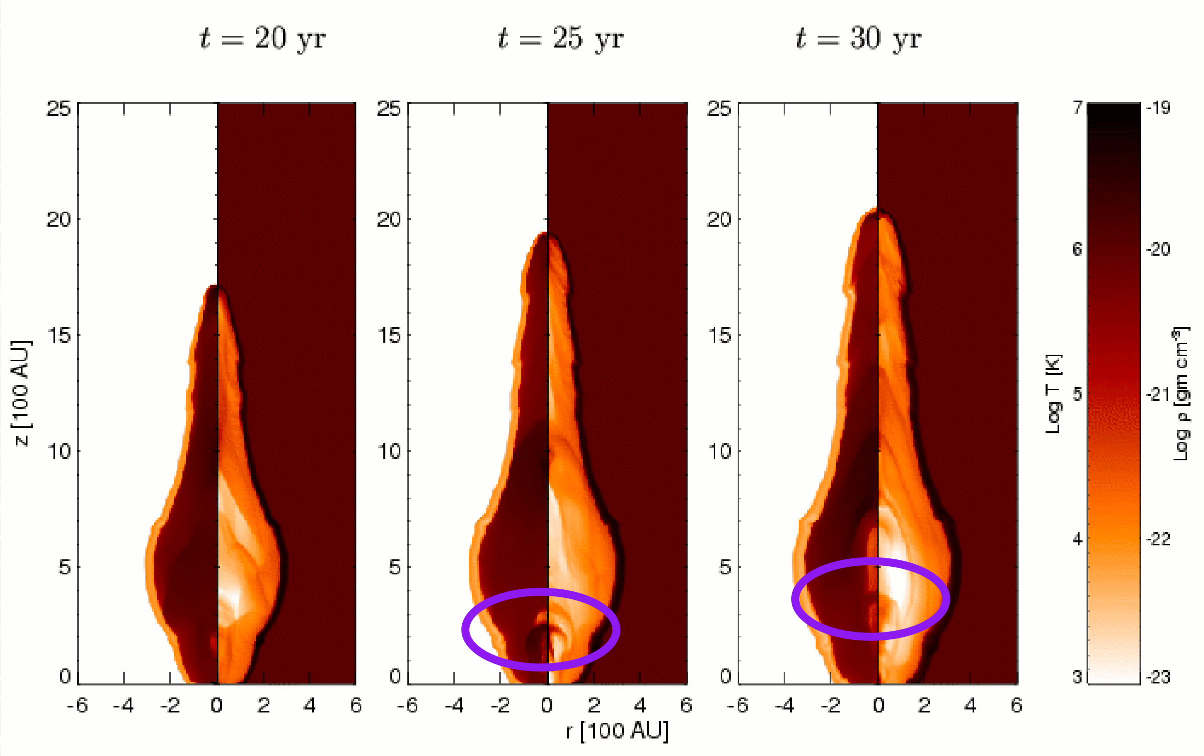
Self-interaction
(Eisloffel's talk; poster De Colle & Caratti o Garatti)

Bonito et al. (2008) in preparation

The pulsed jet scenario

ν	M	v_j [km s^{-1}]	n_a [cm^{-3}]	T_a [10^4 K]
10	500	2300	5000	0.1

- light jet
- high speed



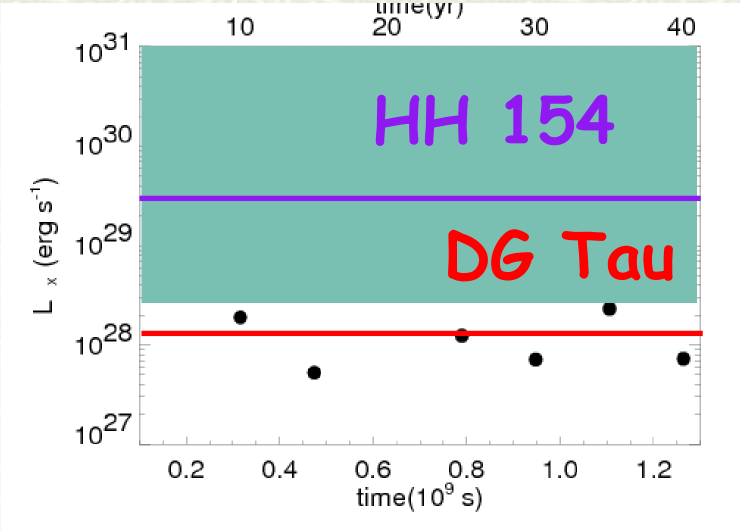
Bonito et al. (2008) in preparation

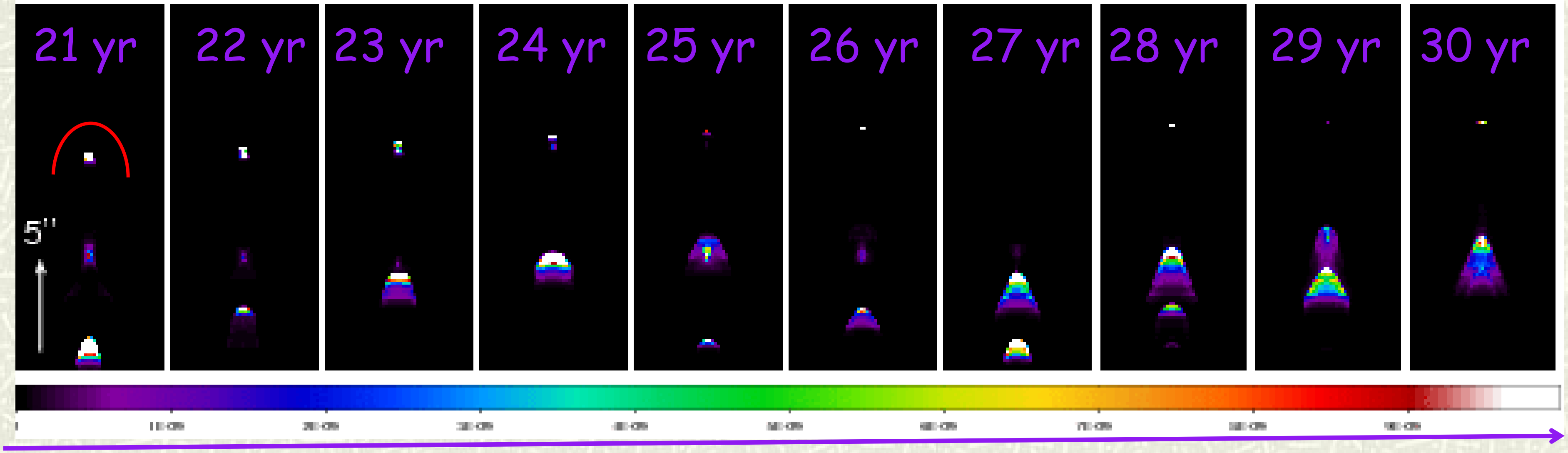
The pulsed jet scenario

cnts	$n_H \pm \Delta n_H$ (10^{22} cm^{-3})	$T \pm \Delta T$ (10^6 K)	$EM \pm \Delta EM$ (10^{52} cm^{-3})	χ^2	Prob.[a]
91	1.40 ± 0.32	3.5 ± 1.7	0.6 ± 2.1	0.195	0.978
10000	1.39 ± 0.02	3.4 ± 0.1	0.6 ± 0.1	0.708	1.000

[a] Null hypothesis probability.

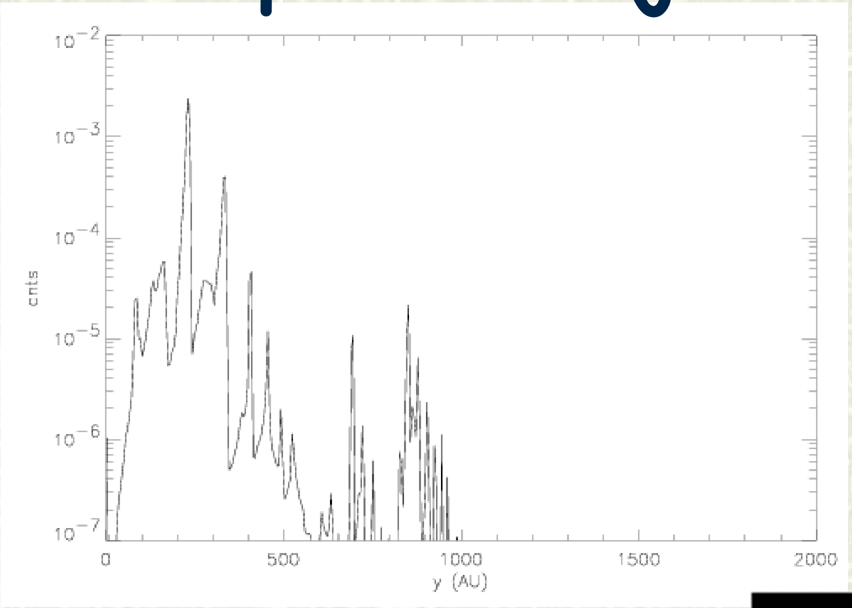
realistic: 100 cnts





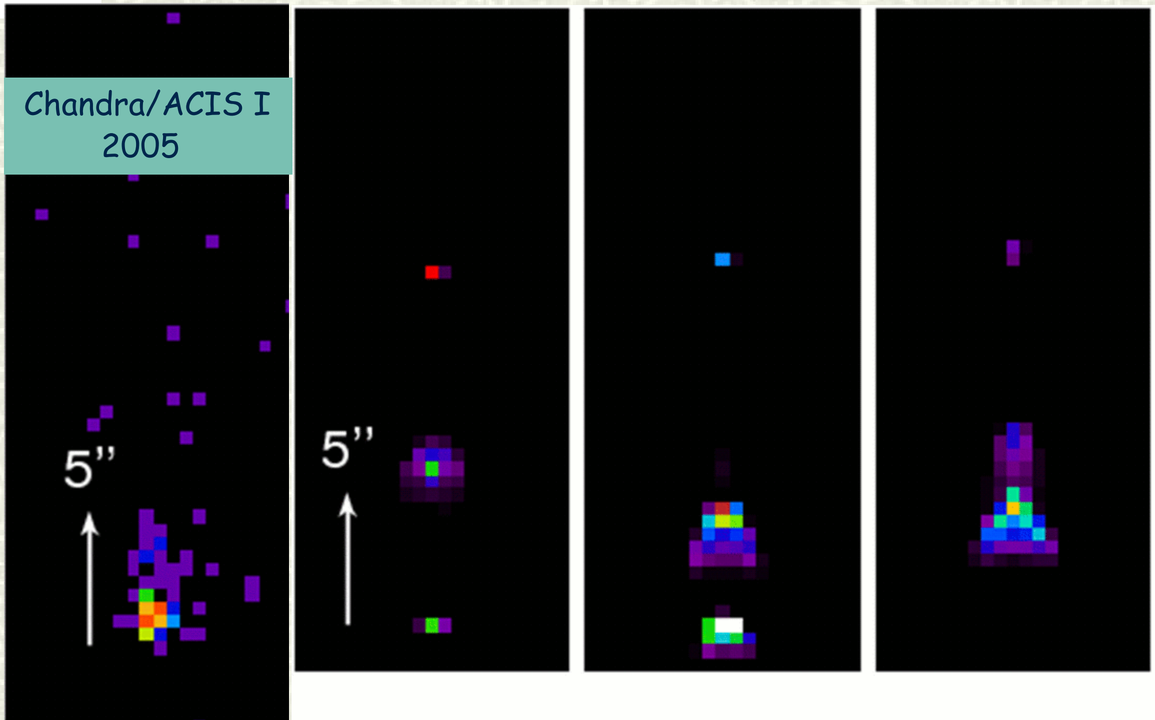
Bonito et al. (2008) in prep.

The pulsed jet scenario



- X-ray from the base of the jet
- Complex morphology
- Variability
- Size of the X-ray source

Bonito et al. (2008) in prep.



Conclusions

- X-ray from the base of the jet
- Complex morphology
- Variability
- $T \sim 10^6$ K
- $L_X \sim (10^{28} - 10^{31})$ erg/s
- $v_{sh} \sim 500$ km/s

} (*) **New features 2005**

- First simple model continuous jet:
  reproduces in a natural way the X-ray emission (T, L_X, v_{sh})
  does not explain (*)
- "New" model to explain (*): $v(t)$
- Exploration of the parameter space:
  M, ν, n_j, $v(t)$, …
- Preliminary results:
  (*) + size in nice agreement with HH 154
  promising model: work in progress