OBSERVATIONS AND MODELING OF X-RAY EMISSION FROM PROTOSTELLAR JETS

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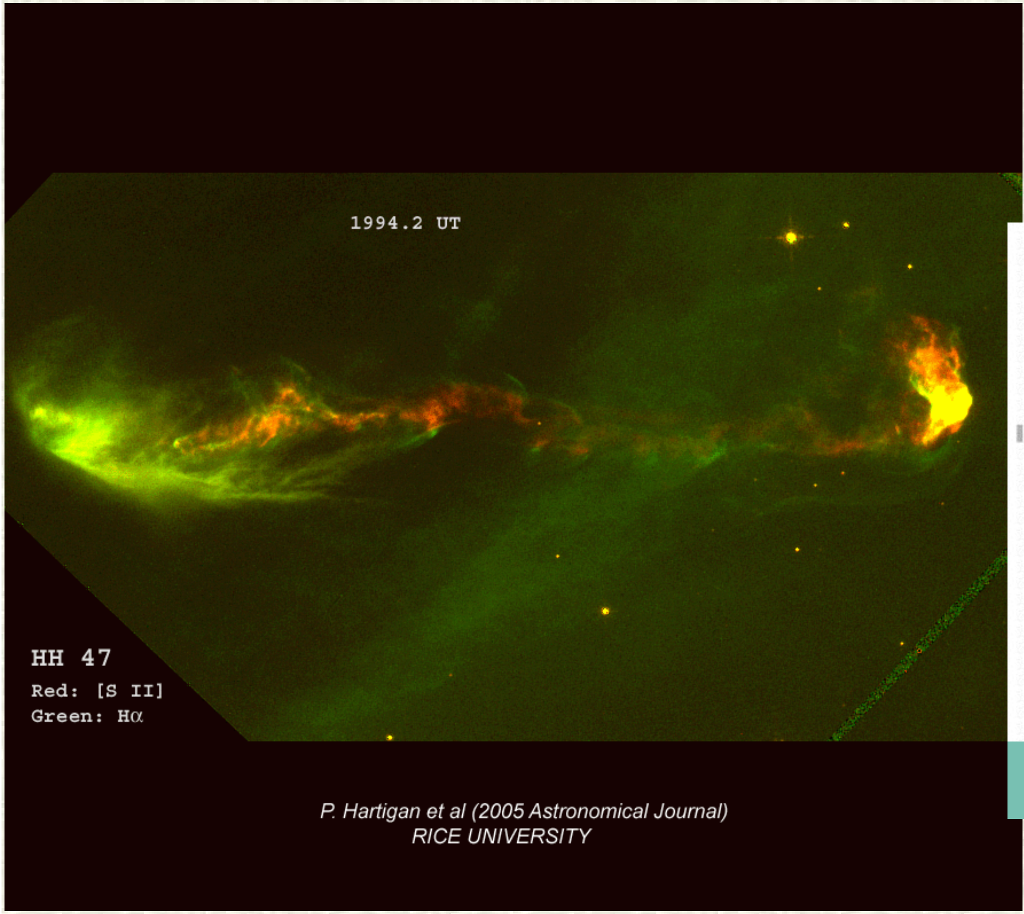
Outline

- 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

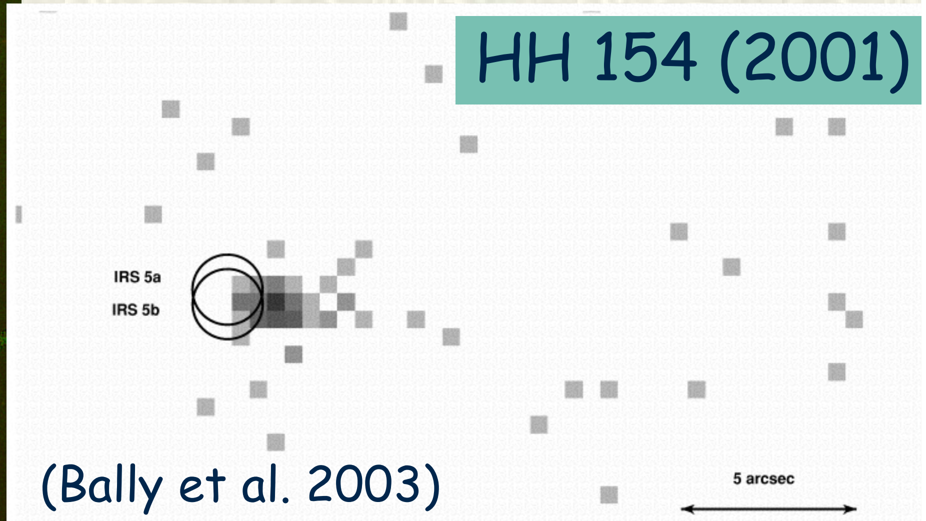


X-ray emission

discovered from few HH objects since 2000:

the first 2 (in 2000):

HH 154 (2001)



(Bally et al. 2003)

Close up view with Chandra ACIS-I

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

X-ray emitting HH jets (few examples)

- 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	Gudel et al. (2008)

Bonito et al. (2007)

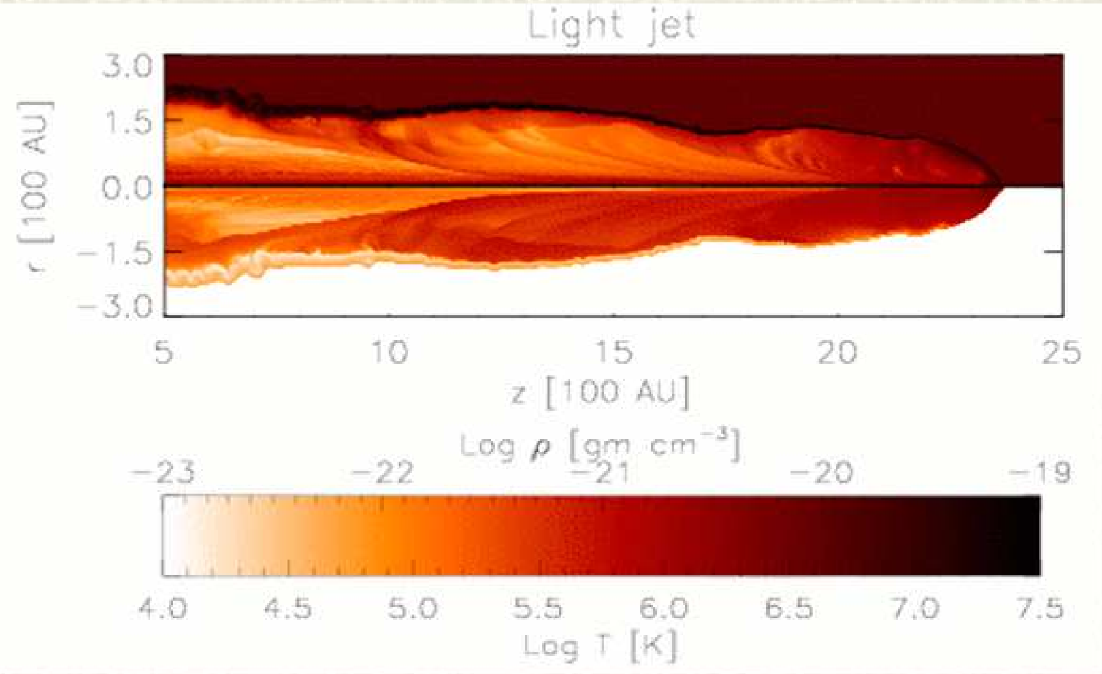
Hydrodynamic evolution

solving the hydrodynamic equations

(with radiative losses and thermal conduction effects)

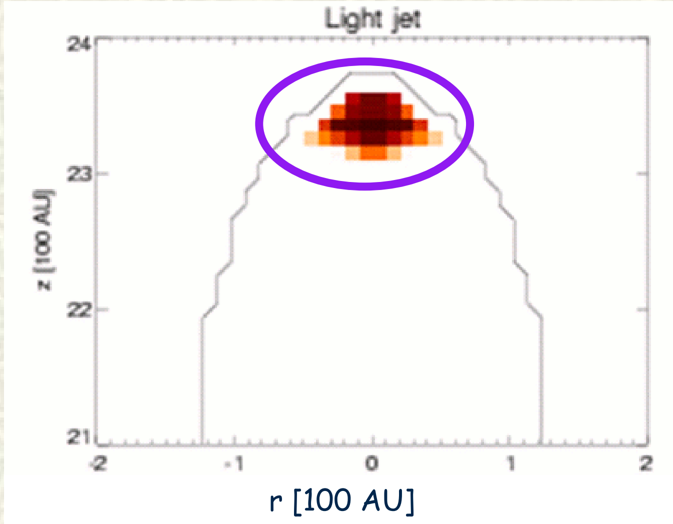
with the FLASH code

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)

(Chandra/ACIS-I)



first X-ray synthesis from protostellar jets

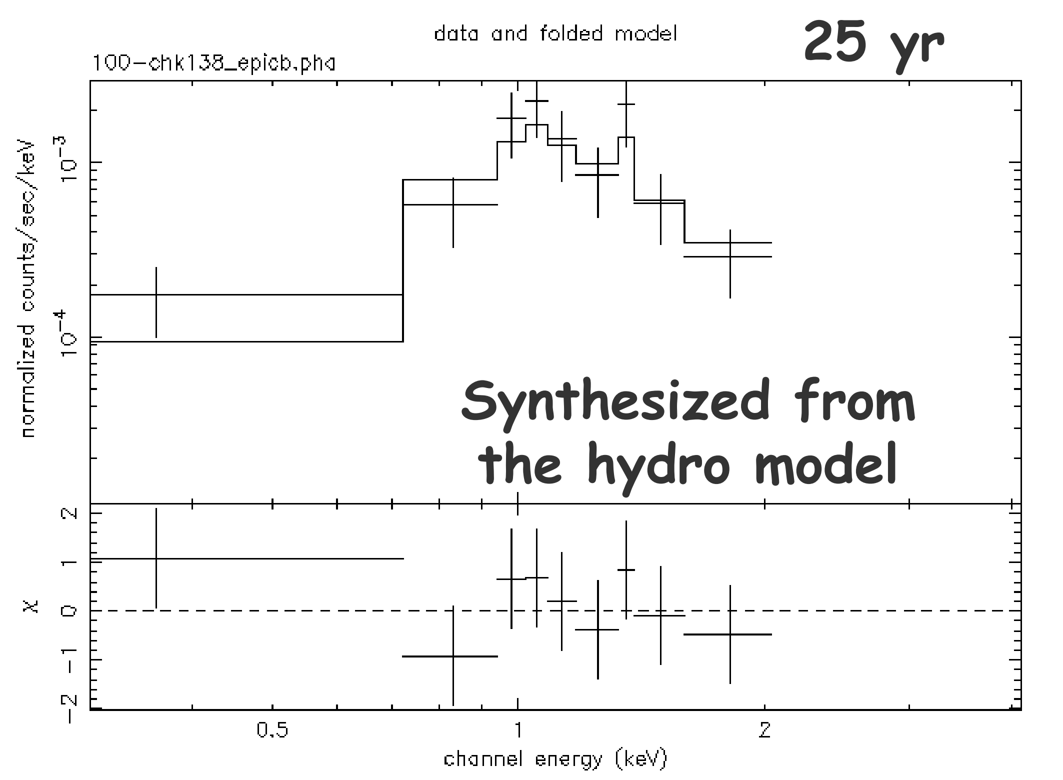
proper motion

of the X-ray source:

$v_{sh} \approx 500$ km/s

X-ray emission from a light jet

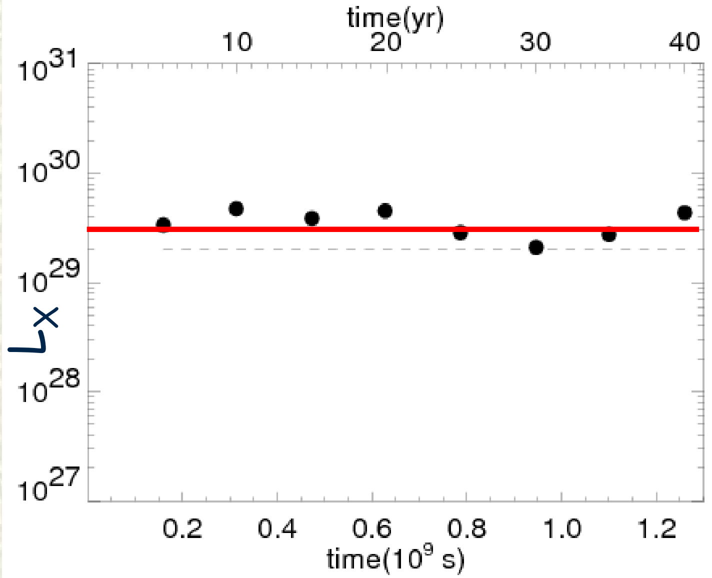
(XMM-Newton/EPIC-pn)




```
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/cm²/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/cm²/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 $(EM, T)_{best\text{-}fit}$

predicts proper motion

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

Model

(Bonito et al. 2004):

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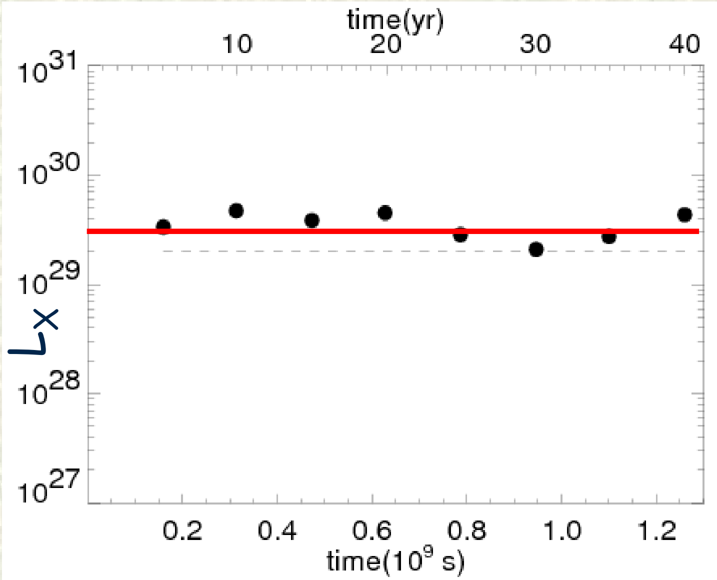
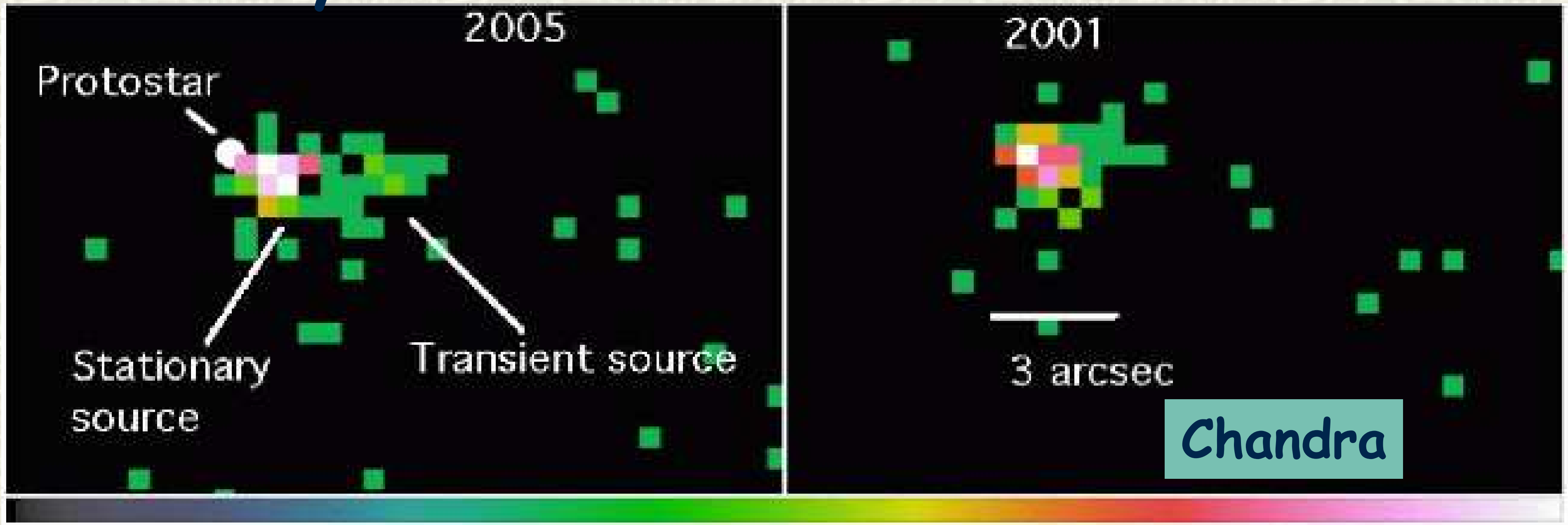


X-ray emission: observations



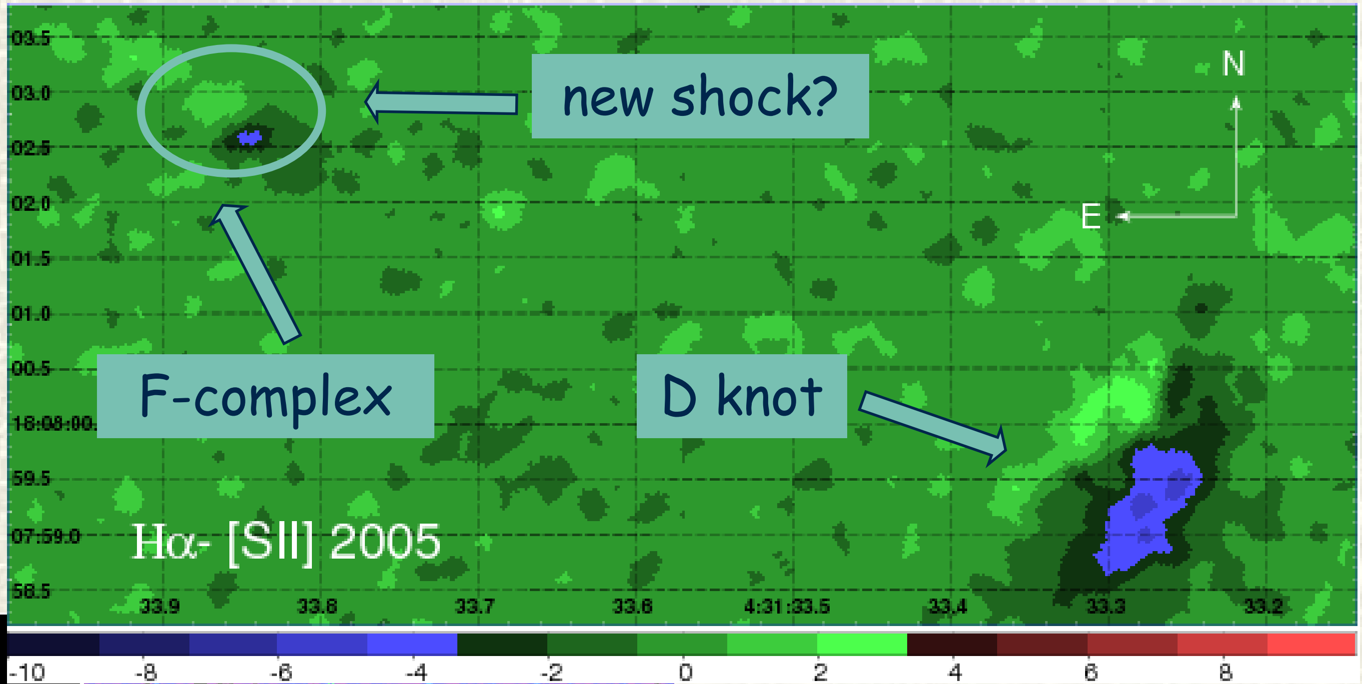
- Complex morphology: two components
1) point-like, stationary (over 4 yr)
2) elongated
- Proper motion elongated X-ray source (component 2):
  as predicted by the model
  detected for the first (and only) time
- Speed consistent with model's results: 460 km/s

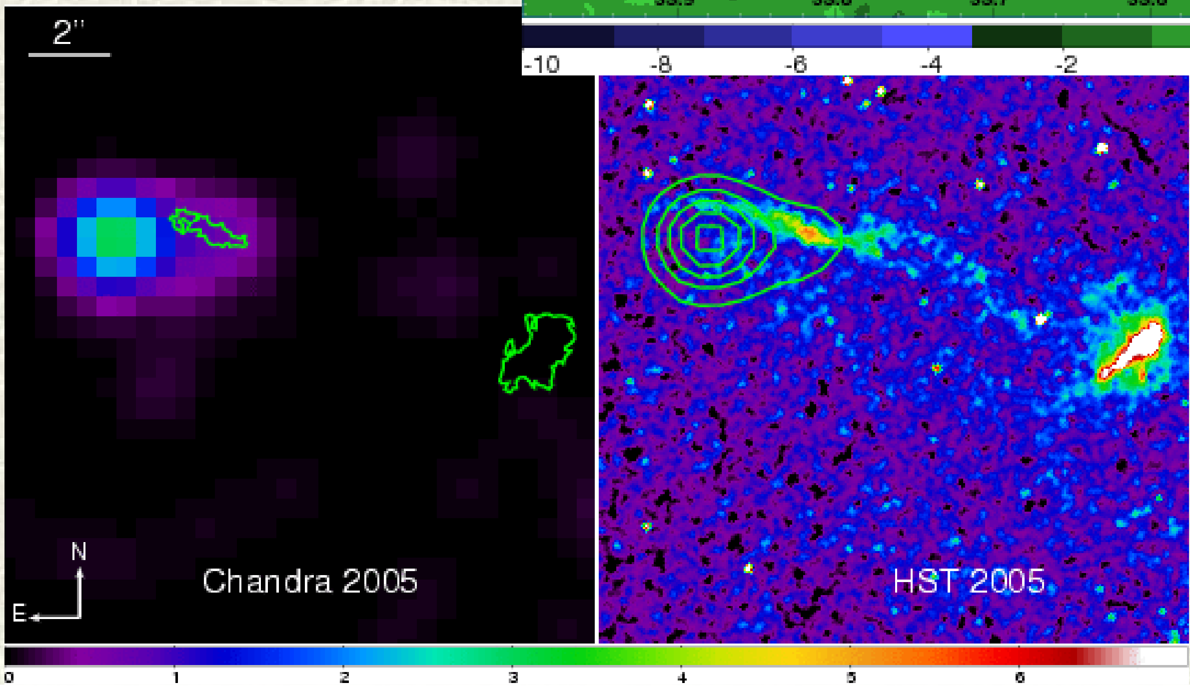
to verify the model

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

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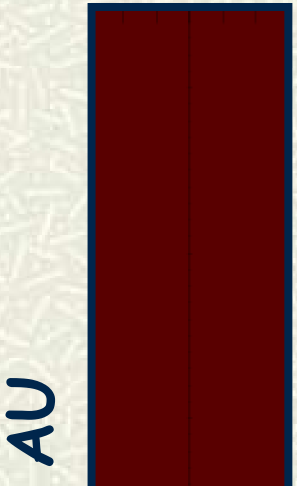
New model to explain:

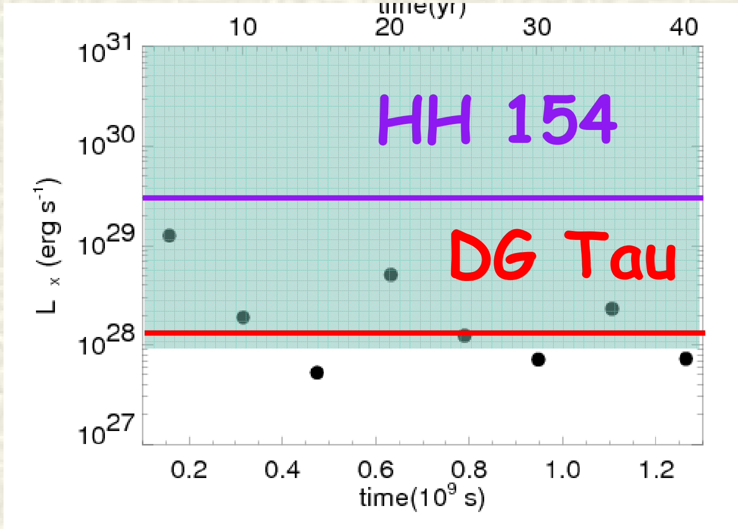
- X-ray emission from the base of the jet (HH 154, DG Tau)
- Complex morphology (the first and only one case = HH 154)
- Variability (the first and only one case = HH 154)

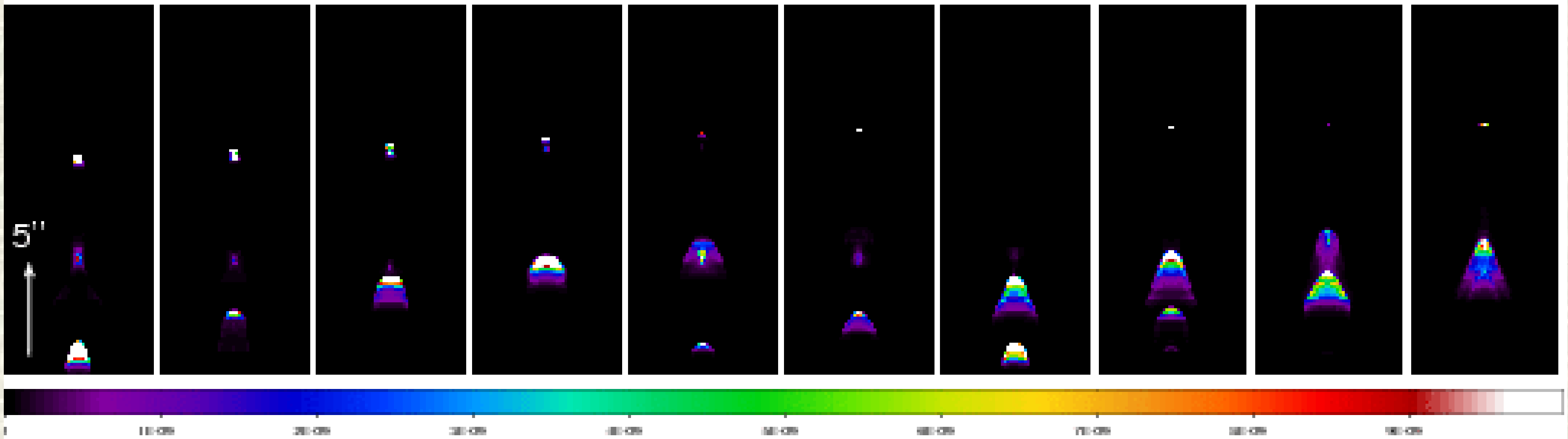
common feature for HH jets

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



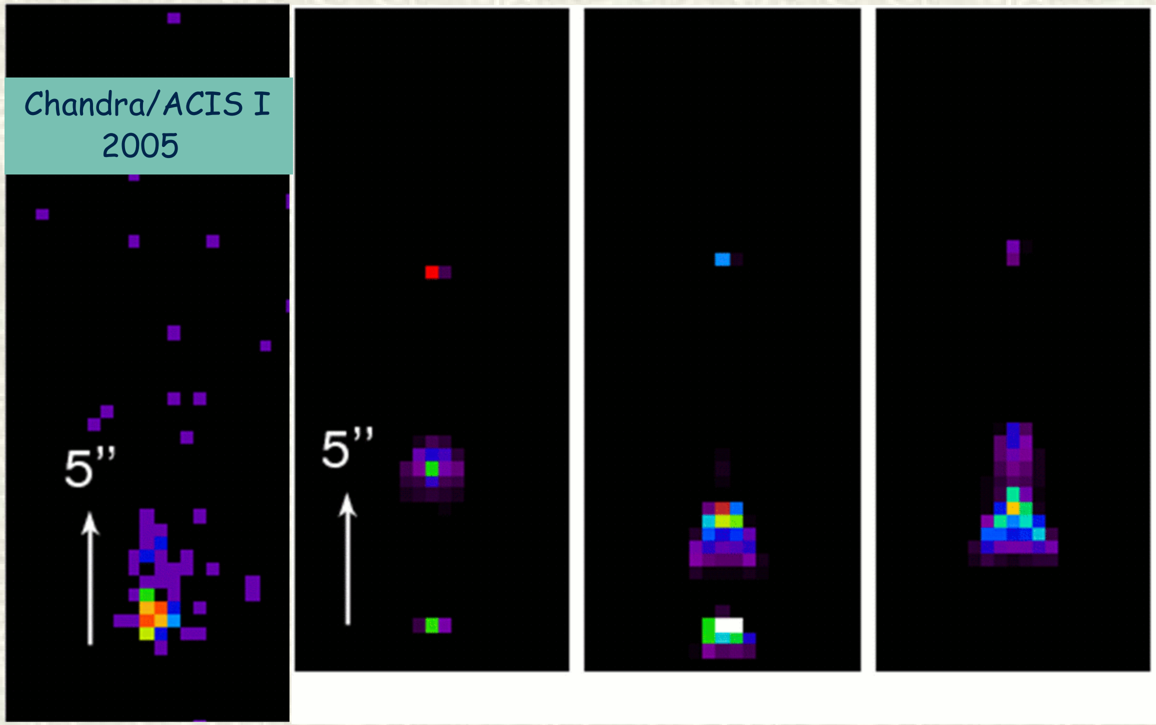




Bonito et al. (2009) in preparation

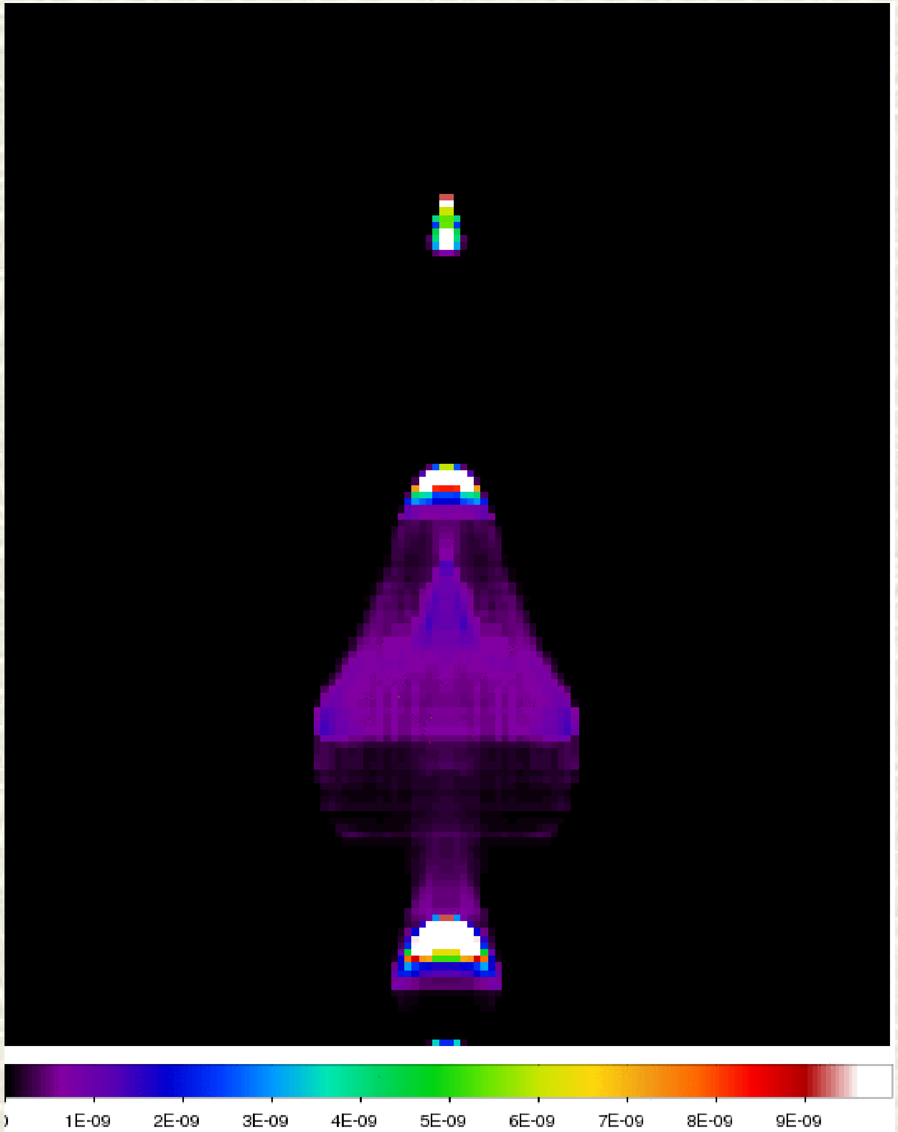
The pulsed jet scenario

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



Bonito et al. (2009) in prep.

The pulsed jet scenario



Bonito et al. (2009) in prep.

Conclusions

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

} (*)

- T ~ 10^6 K
- L_X ~ (10^{28} - 10^{31}) erg/s
- $v_{sh} \approx 500$ km/s
- 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