Internal shock waves in jets and their connection with astrophysical cosmology.

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Colegio Nacional

Mexico City
JULY 20, 2010

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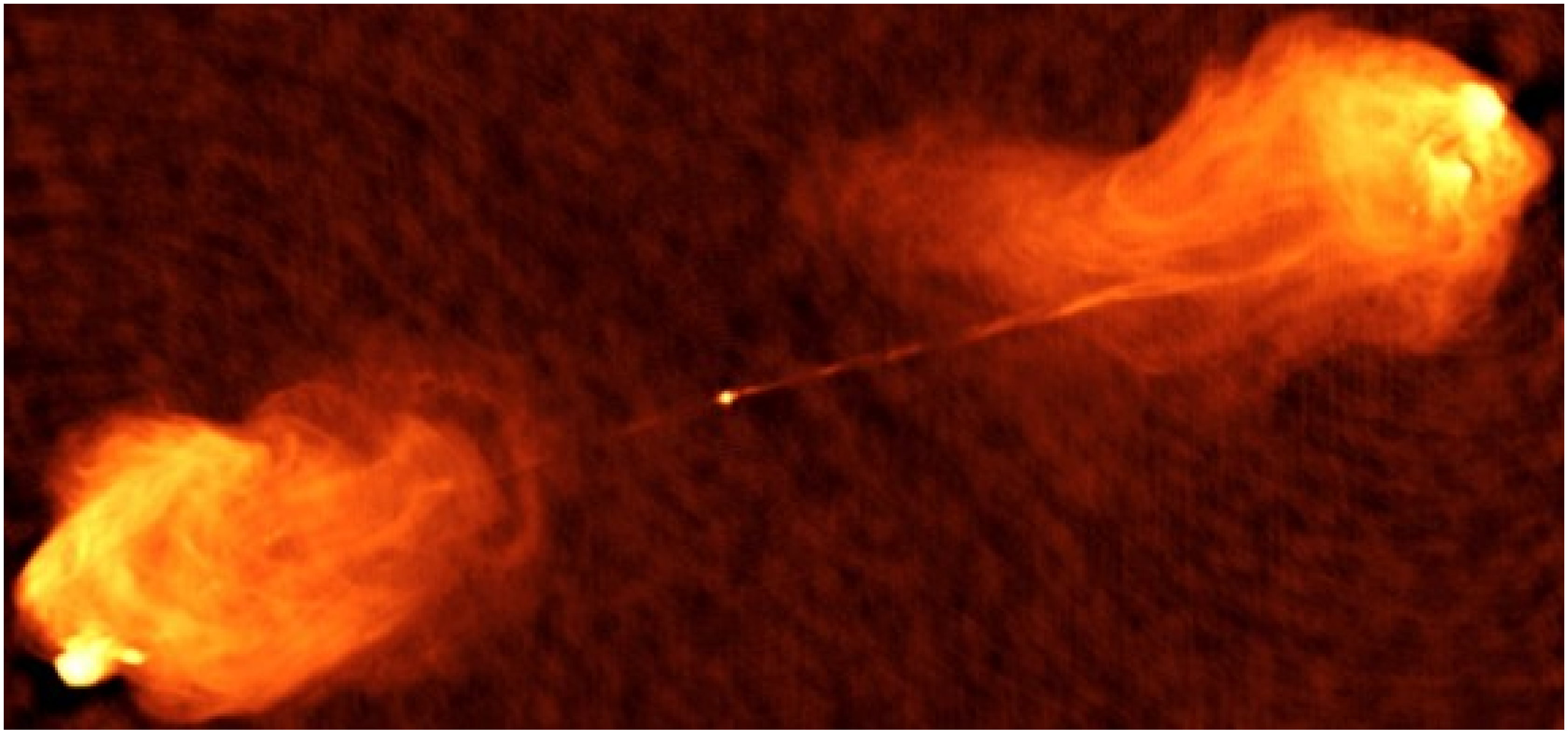
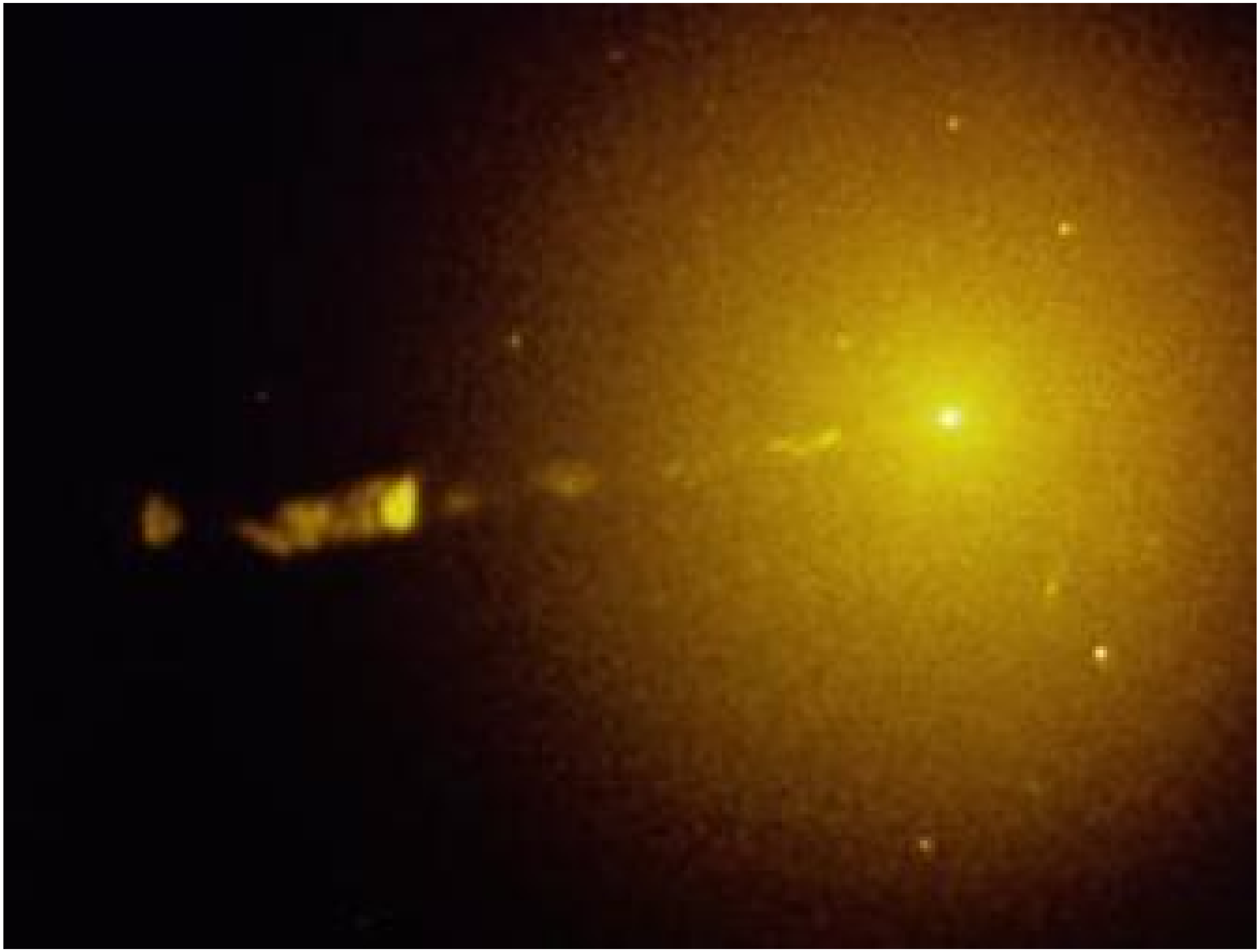
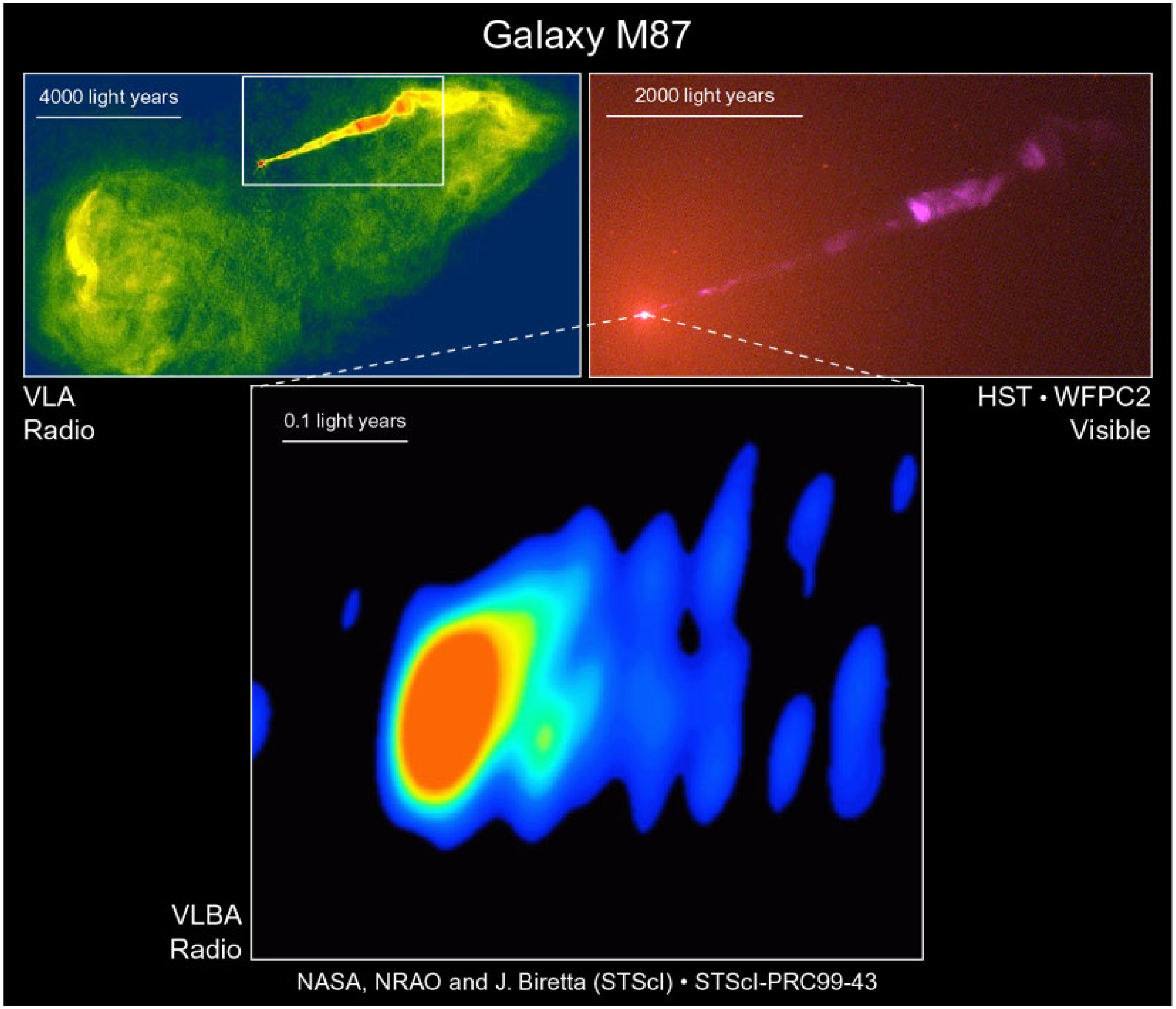


1 Jets

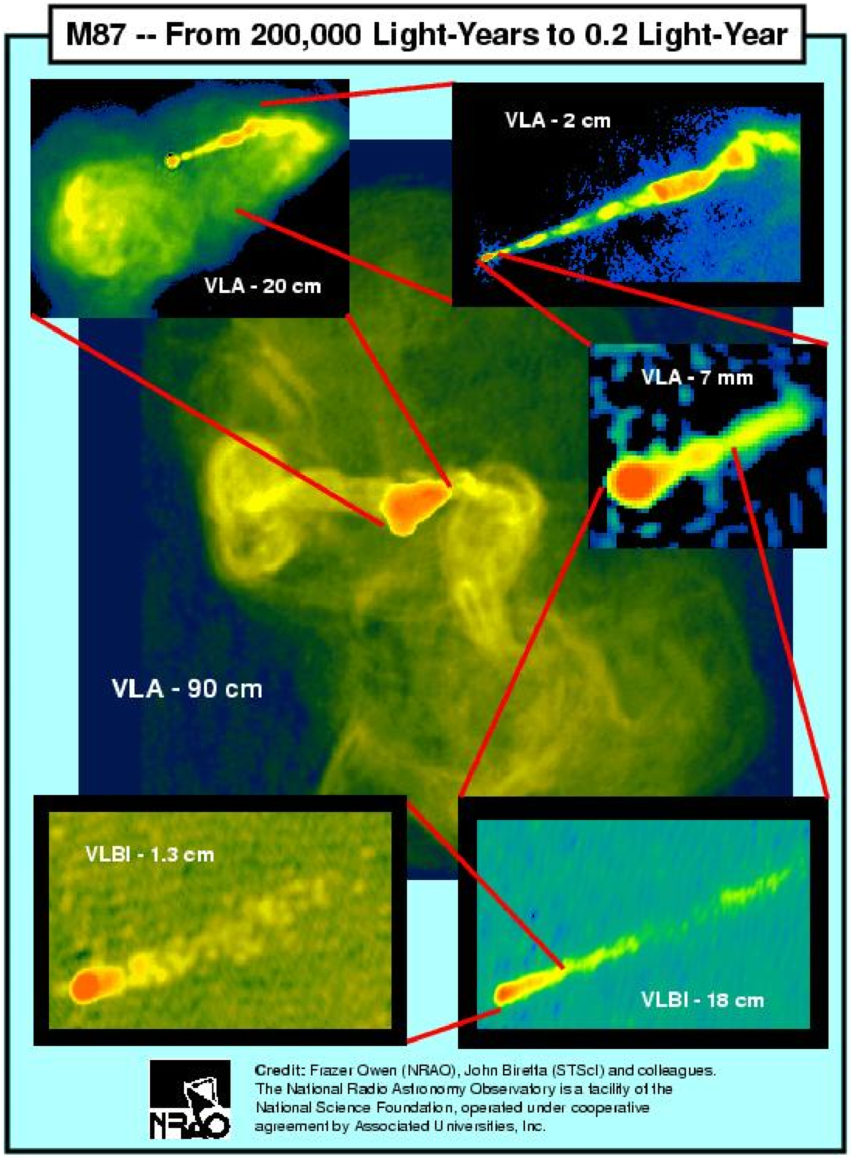
- ☆ In 1781, Charles Messier optically discovered galaxy *M87* (NGC 4486, 3C 274 or Virgo A).
- ☆ In 1918, Heber Curtis described a "*curious straight jet . . . apparently connected with the nucleus by a thin line of matter*
- ☆ Unfortunately Curtis' observations were not followed up to the 1950's and 1960's with the development of *radio astronomy*
- ☆ In 1953, Ginzburg & Shklovski suggested that the radiation was due to synchrotron processes after Baade showed that it was strongly polarised.
- ☆ Immediately Burbidge calculated the minimum energy contained in relativistic electrons and the magnetic field of Cygnus A, with the surprising result: ¡3×10^{58}ergs!
- ☆ Following decades showed that many galaxies (mainly at large redshifts ~ 2) had radio jets.
- ☆ Central engine: supermasive black hole (Novikov & Zeldovich 1964).



M87 as seen by the HST.



M87 at different scales and wavelengths.


M87 -- From 200,000 Light-Years to 0.2 Light-Year
VLA - 20 cm
VLA - 2 cm
VLA - 7 mm
VLA - 90 cm
VLBI - 1.3 cm
VLBI - 18 cm
Credit: Frazer Owen (NRAO), John Biretta (STScI) and colleagues.
The National Radio Astronomy Observatory is a facility of the
National Science Foundation, operated under cooperative
agreement by Associated Universities, Inc.

2 Relativistic hydrodynamics

- Perfect fluid. Quantities measured on the proper system of reference.
- Quantities measured per unit volume.
- Gravity is given: $g_{\mu\nu}$

$$\nabla_\mu \left(n u^\mu\right) = 0, \qquad \text{(continuity)} \tag{1}$$

$$\nabla_\mu T^{\mu\nu} = 0, \qquad \text{(energy-momentum)} \tag{2}$$

$$\nabla_\mu \left(\sigma u^\mu\right) = 0, \qquad \text{(entropy)} \tag{3}$$

$$w u^\mu \nabla_\mu u_\nu = \partial_\nu p - u_\nu u^\mu \partial_\mu p. \qquad \text{(Euler)} \tag{4}$$

- Enthalpy density: $w = e + p$, $T_{\mu\nu} = w u_\mu u_\nu + p g_{\mu\nu}$.
- Polytropic relation: $p \propto n^\kappa$

$$e = mnc^2 + \varepsilon = mnc^2 + p/\left(k+1\right) \tag{5}$$

- Extremely energetic flows (ultrarelativistic at the microscopic level): $\epsilon \ll p$ $\Rightarrow p = (\kappa + 1)$ (Bondi-Wheeler equation).

3 Shock waves

- ☆ Strong discontinuity of a flow at supersonic velocities.
- ☆ Flux conservation of particle, momentum and energy with a particle flux through the discontinuity.
- ☆ Taub's conditions (relativistic Hugoniot jump conditions)
- ☆ Very general arguments imply that:

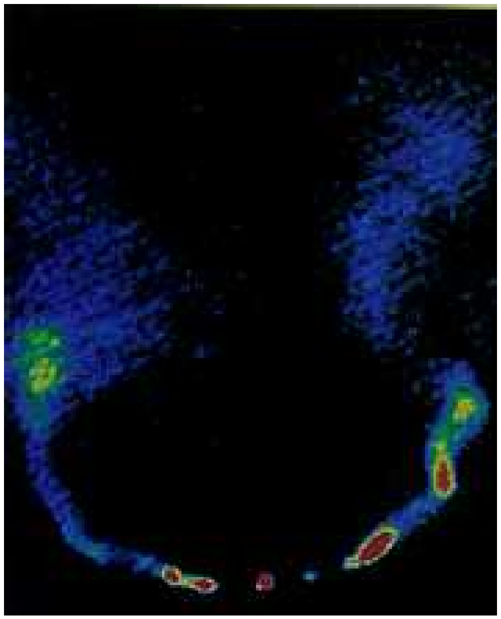
$$p_2 > p_1, \qquad n_2 > n_1, \qquad v_1 > a_1, \qquad v_2 < a_2$$

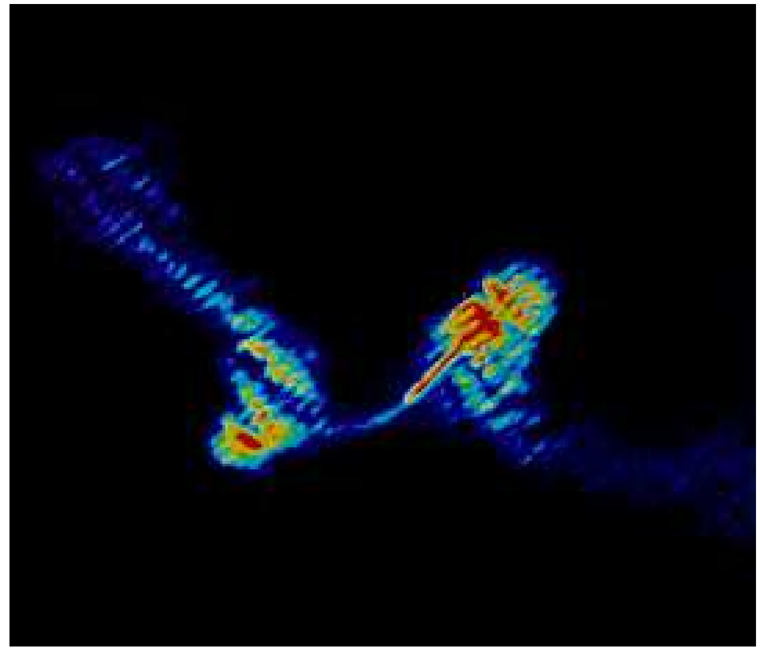
- ☆ McKee & Colgate (1973) developed jump conditions adequate to any system of reference.

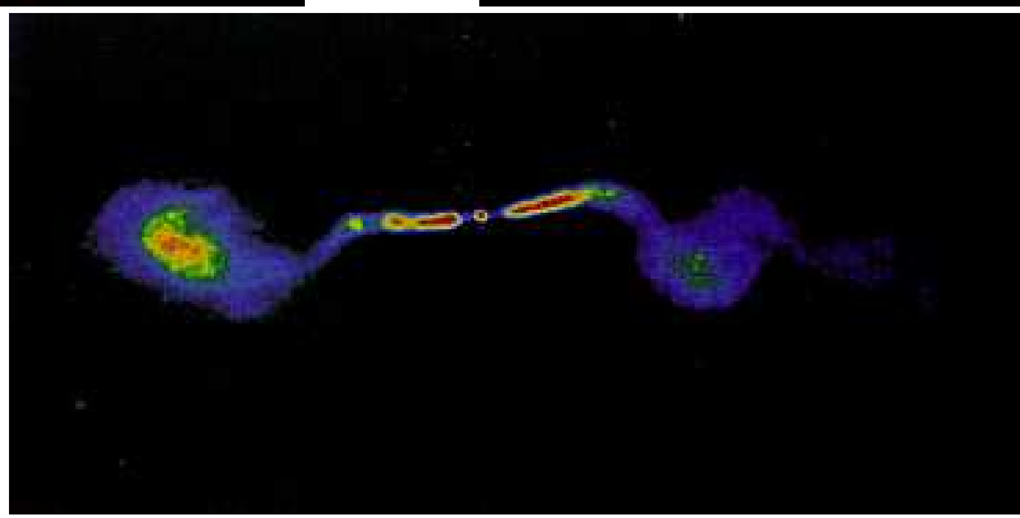
$$\frac{e}{\rho} = \frac{\gamma}{\rho_1}\left[e_1 + p_1\frac{\beta}{\beta_{\mathrm{s}}}\right], \qquad \frac{n}{n_1} = \gamma\frac{\kappa}{\kappa - 1} + \frac{1}{\kappa - 1},$$

$$\Gamma = \frac{\gamma}{\sqrt{1 - 2\left(\kappa - 1\right)/\kappa}}.$$

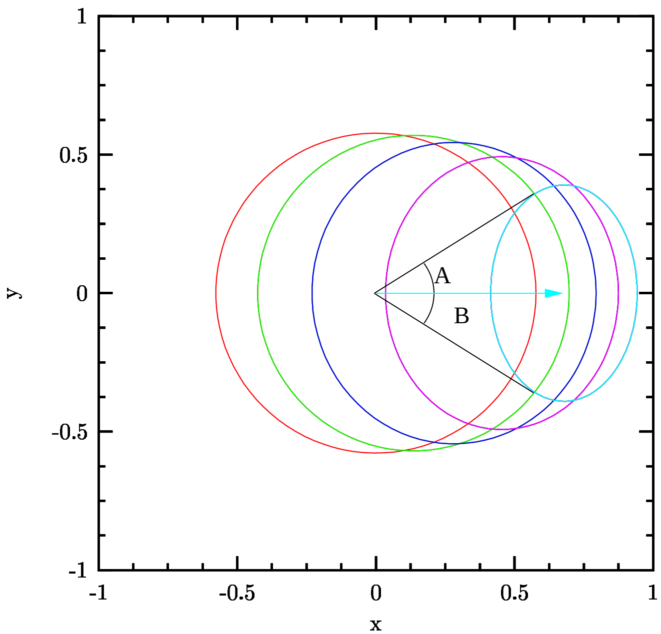
4 Bent jets

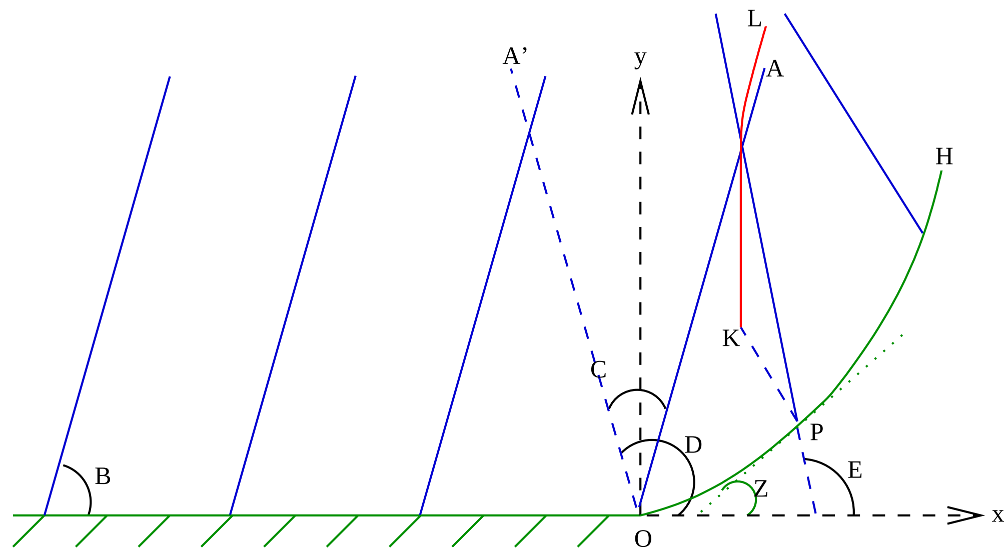






☆ Characteristics. Mach number: $M = 1/\sin\alpha = \gamma v/\gamma_a a$





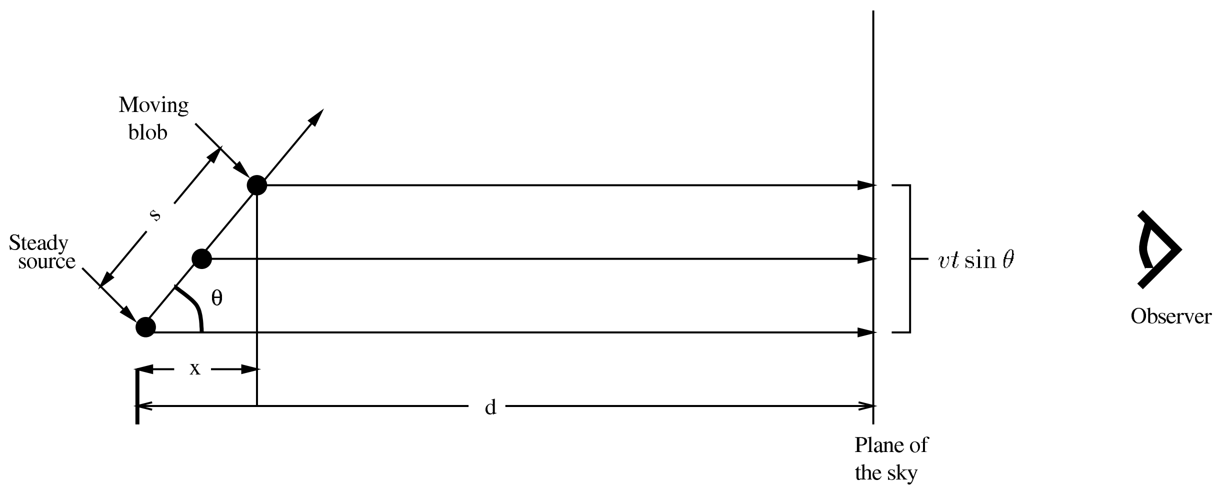
☆ Maximum deflection angle given by (Mendoza & Longair 2002):

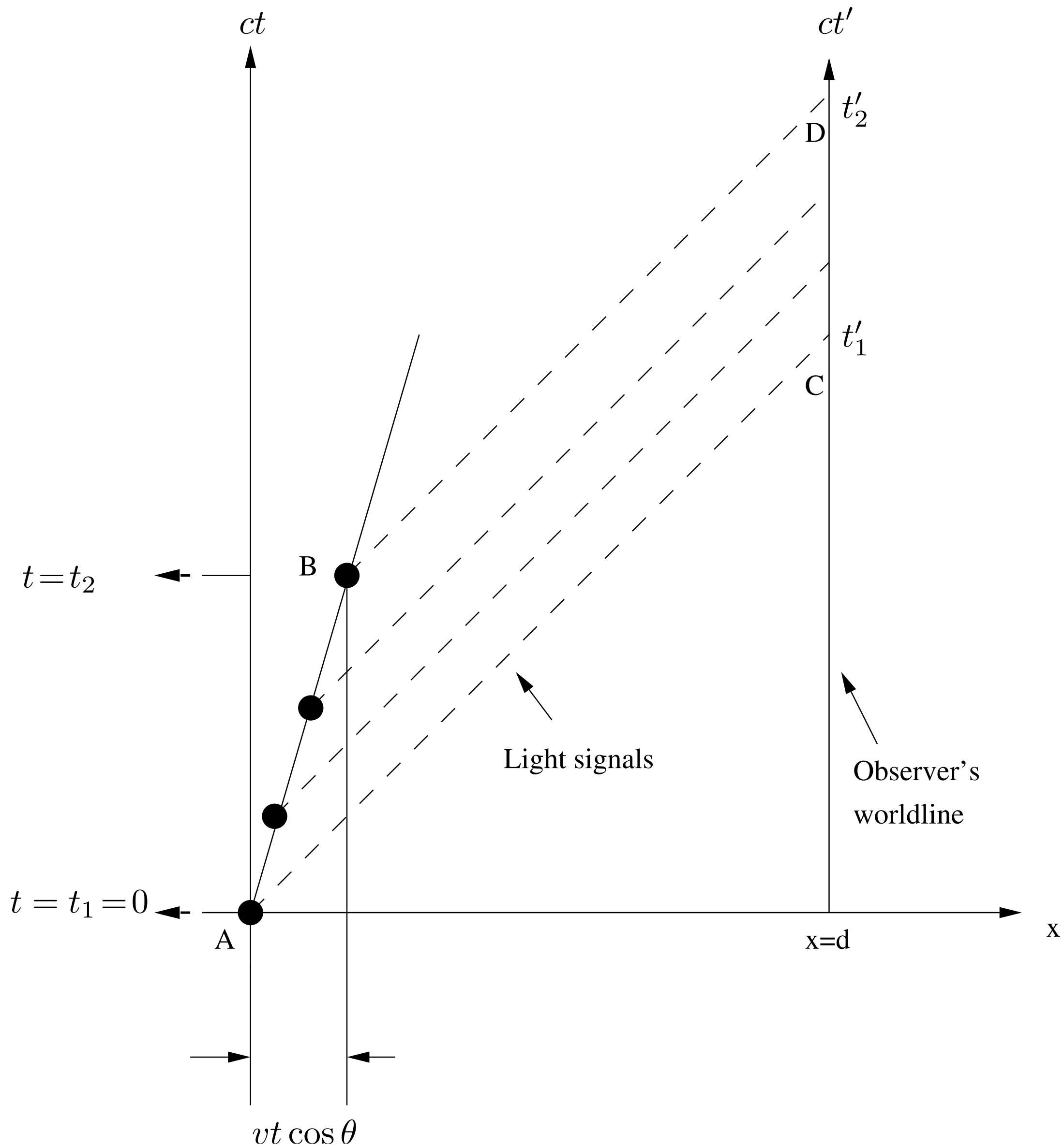
$$\theta_{\max} = \begin{cases} 74.21^\circ & \text{Relativistico, } \kappa = 5/3 \\ 47.94^\circ & \text{Relativistico, } \kappa = 4/3 \\ 134.16^\circ & \text{Newtoniano, } \kappa = 4/3 \end{cases}$$

☆ The more relativistic a jet is, more difficult it is to bent it (Mendoza & Longair 2001).

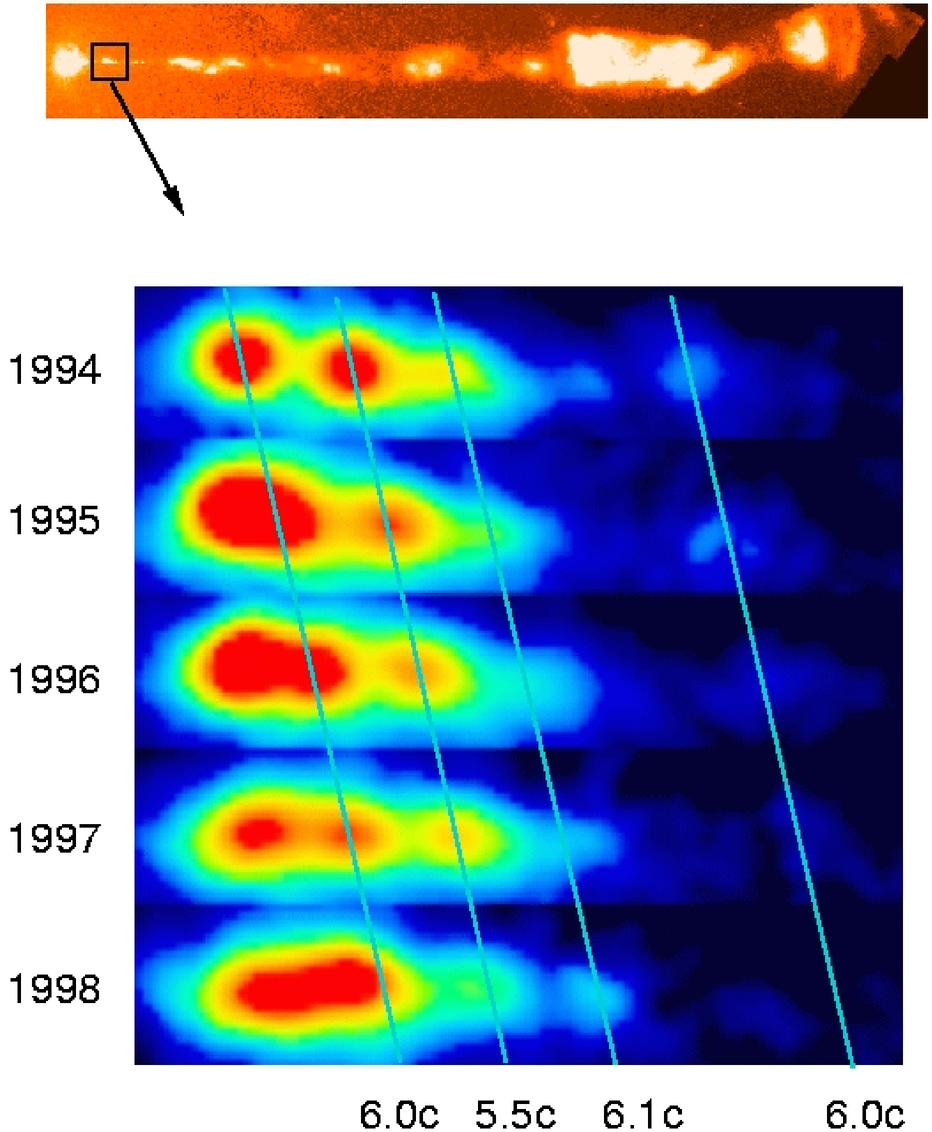
5 Apparent superluminal motion in relativistic jets

- ☆ Theoretical prediction by Rees (1966).
- ☆ There are sources in the sky which apparently move at velocities greater than light.
- ☆ Problem: astronomers measure velocity as observed distance divided by measured time.
- ☆ Solution: a projection problem on the sky due to relativistic motions very close to the speed of light: ($v \sim 0.9c$).



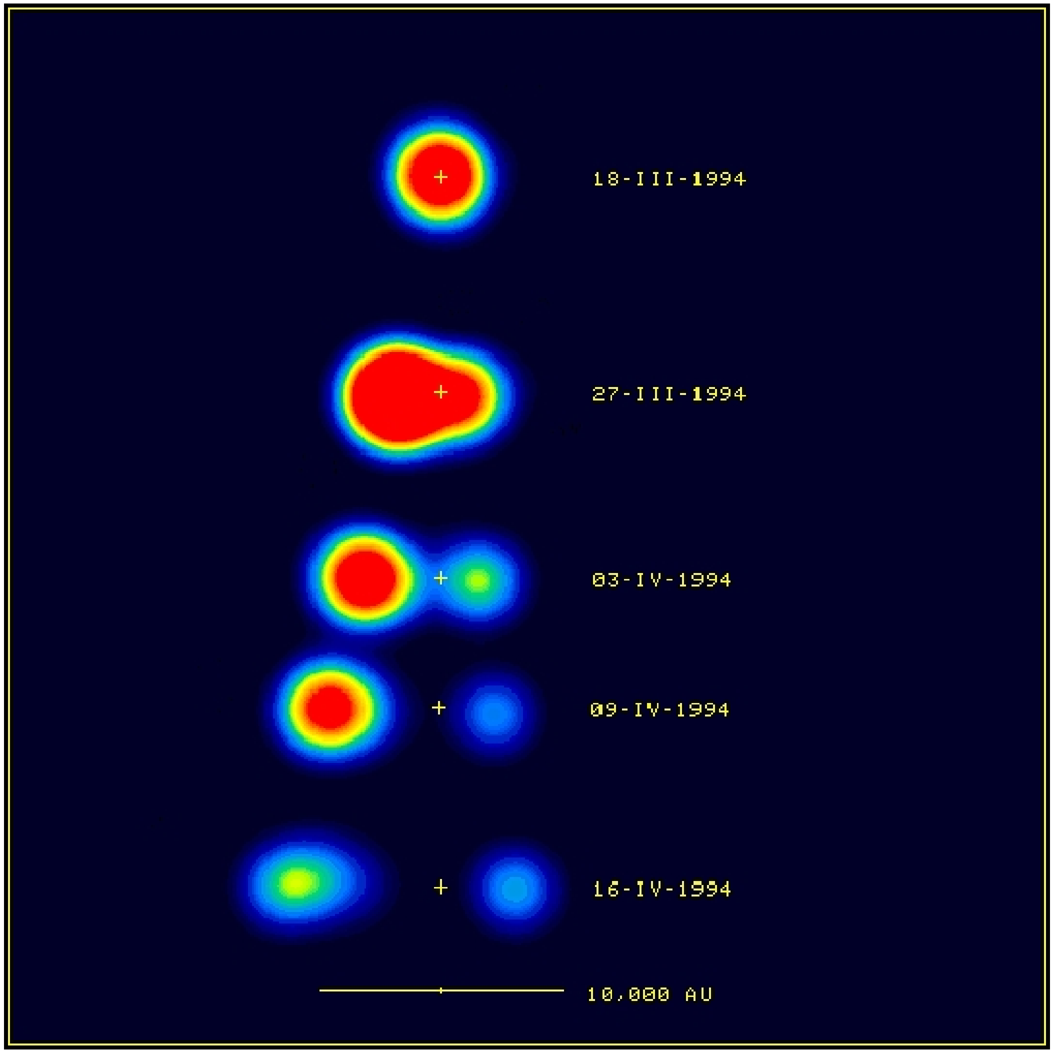


Superluminal motion on a space-time diagram (Mendoza 2003)



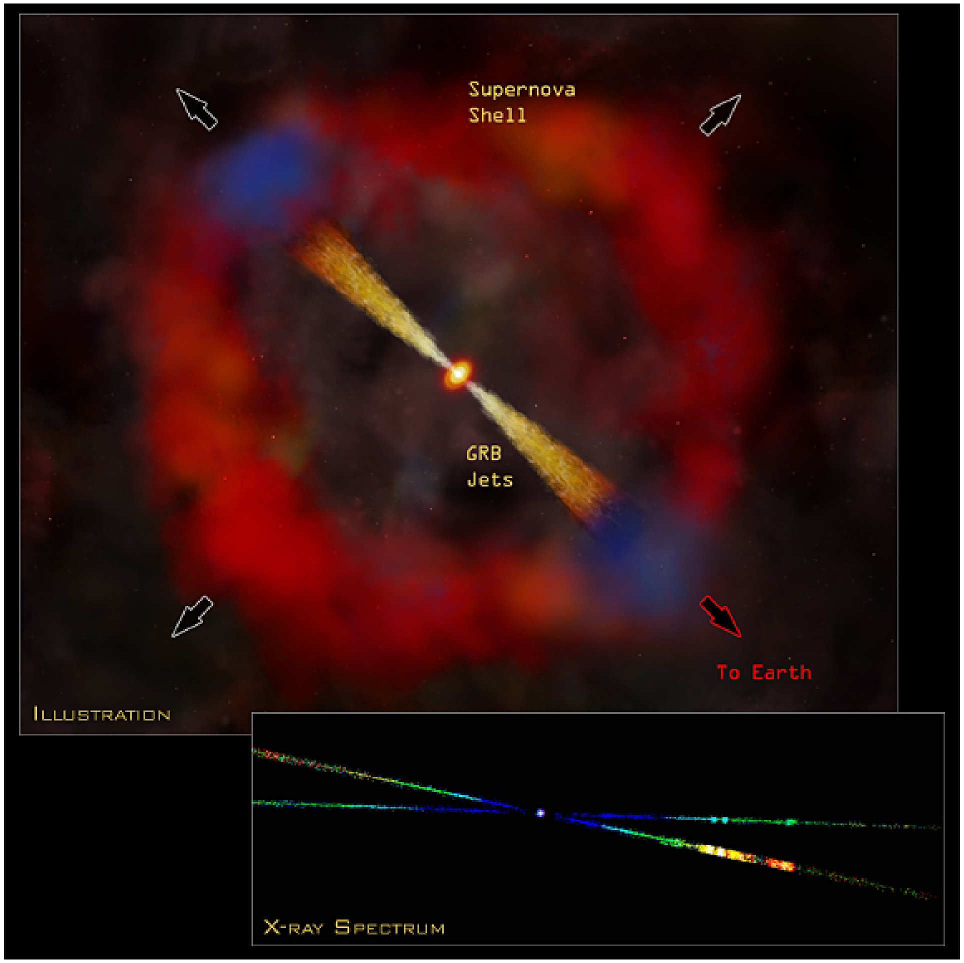
Apparent superluminal motion on M87's jet

6 Micro–QSR jets



Superluminal source (micro–quasar) GRS 1915+105 by Mirabel & Rodríguez (1994)

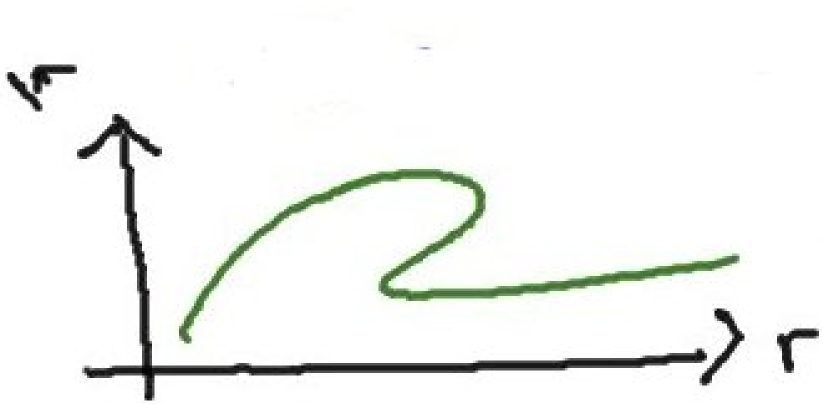
7 Long γ–ray bursts



✔ Light curves of long γ–ray bursts are produced by shock waves (as the ones produced by apparent superluminal motion).

8 Analytic model

- Cantó, et. al (2000) & Cantó, et. al (2003) made non–relativistic models with ballistic approximations on the working surfaces inside jets.
- Mendoza, Hidalgo et al. (2009) generalised this model to the relativistic regime as follows.
- Analysis in 1D.
- Velocity $u(\tau)$ with mass discharge $\dot{m}$.
- Ejection mechanism behaves as free streaming.
- In this case a working surface is formed due to the fact that fast flow overtakes slow fluid particles.



=> INITIAL DISCONTINUITY

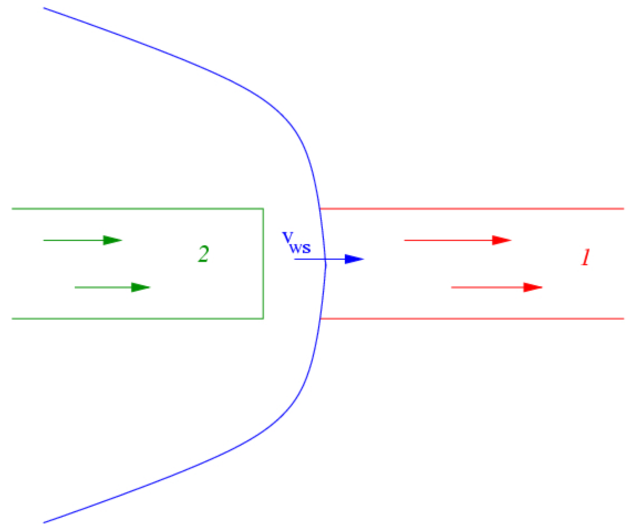
☆ Assume that:

$$u_1 := u_1(\tau_1), \qquad u_2 := u_2(\tau_2) = u_1 + \alpha \Delta t. \tag{6}$$

$\Rightarrow$ if $\alpha > 0$ then a working surface is formed.

☆ Finally, consider *no mass loss* of a *thin* working surface.

☆ The position of the centre of mass is given by



- Upstream flow: $x_{\text{ws}} = u_1(t - \tau_2)$
- Downstream flow: $x_{\text{ws}} = u_2(t - \tau_2)$

9 Dynamics of the working surface

- ☆ Velocity of the working surface = velocity of the centre of mass, i.e.

$$v_{\rm ws} = \frac{1}{M_\gamma}\int_{\tau_1}^{\tau_2} \gamma\left(u(t)\right)\dot{m}(t)u(t){\rm d}t, \qquad (7)$$

with a "weighted" mass

$$M_\gamma = \int_{\tau_1}^{\tau_2} \gamma\left(u(t)\right)\dot{m}(t){\rm d}t. \qquad (8)$$

- ☆ With all these, the position of the shock wave is given by

$$x_{\rm ws} = (t-\tau_2)v_{ws} + \frac{1}{M_\gamma}\int_{\tau_1}^{\tau_2} \gamma\left(u(t)\right)\,\dot{m}(t)\,u(t)\,(t-\tau_2)\,{\rm d}t. \qquad (9)$$

- ☆ These equations are parametrised by τ_2 only.

- Initial energy of the flow is

$$E_0 = \int_{\tau_1}^{\tau_2} \dot{m}(\tau)\, \gamma\left(u(\tau)\right)\, c^2 \mathrm{d}\tau, \tag{10}$$

- Energy inside the working surface is $E_{\mathrm{ws}} = m \gamma_{\mathrm{ws}} c^2$.
- The energy loss is then $E_{\mathrm{r}} = E_0 - E_{\mathrm{ws}}$.
- If all this energy is radiated away, then

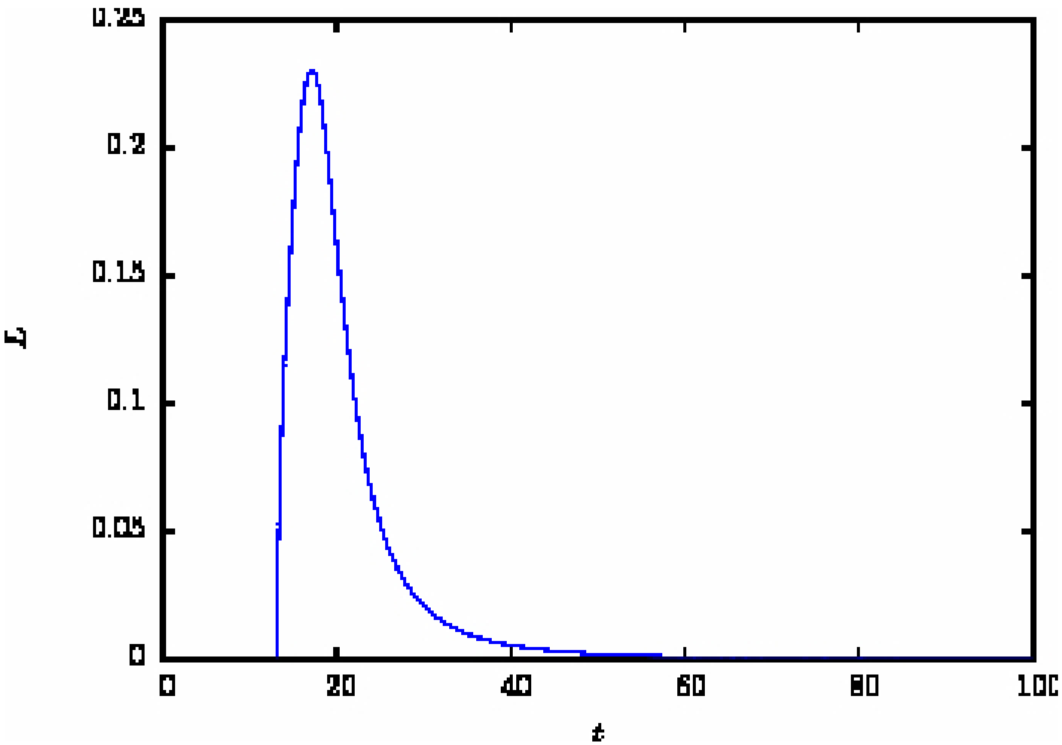
$$\begin{aligned} L &= \frac{\mathrm{d}E_{\mathrm{r}}}{\mathrm{d}t} \\ &= \frac{\dot{m}(\tau_2)}{\mathrm{d}t/\mathrm{d}\tau_2} \left\{ \gamma_{\mathrm{ws}} + \frac{m}{M_\gamma} \gamma_{\mathrm{ws}}^3 \gamma_2 \left(v_{\mathrm{ws}} v(\tau_2) - v_{\mathrm{ws}}^2 \right) - \gamma_2 \right\} - \\ &- \frac{\dot{m}(\tau_1)}{\mathrm{d}t/\mathrm{d}\tau_2} \frac{\mathrm{d}\tau_1}{\mathrm{d}\tau_2} \left\{ \gamma_{\mathrm{ws}} + \frac{m}{M_\gamma} \gamma_{\mathrm{ws}}^3 \gamma_1 \left(v_{\mathrm{ws}} v(\tau_1) - v_{ws}^2 \right) - \gamma_1 \right\}, \\ &= F\left(\dot{m}(\tau_{1,2}), \gamma_{1,2,\mathrm{ws}}, u(\tau_{1,2}), v_{\mathrm{ws}}; \tau_2 \right). \end{aligned} \tag{11}$$

10 A simple example

- $1 = c = \dot{m} = w$, with an oscillating frequency w such that $[w] = 1/t$. This means that

$$[L] = [\dot{m}].v(\tau) = 0.99 - \epsilon^2 \sin\tau, \qquad \epsilon^2 = 0.09$$

- Analytical solution is possible to $O(\gamma^{-1})$ but quite cumbersome!!!
- Semi-analytic solutions are easy (with the aid of the GSL C library).



11 aztekas.org

- ☆ Aztekas code (Mendoza, Olvera, ... 2009)
- ☆ The code is free (in the sense of the Free Software Foundation -GPL license), written on C. It uses maxima, gsl, perl, bash, gnuplot, mencoder & compiled with gcc.
- ☆ At the moment it is capable of solving the 1DRHD using finite differences and artificial viscosity in planar and spherical symmetries.
- ☆ Keep an eye on the site for further updates.

$$\frac{\partial \gamma n}{\partial t} + \frac{1}{r^k}\frac{\partial \gamma n v}{\partial r} = 0, \tag{12}$$

$$\frac{\partial}{\partial t}\left(\frac{e+v^2 p}{1-v^2}\right) + \frac{1}{r^k}\frac{\partial}{\partial r}\left[r^k v \frac{p+e}{1-v^2}\right] = 0, \tag{13}$$

$$\frac{\partial}{\partial t}\left(v\frac{p+e}{1-v^2}\right) + \frac{1}{r^k}\frac{\partial}{\partial r}\left[r^k v^2 \frac{p+e}{1-v^2}\right] + \frac{\partial p}{\partial r} = 0. \tag{14}$$

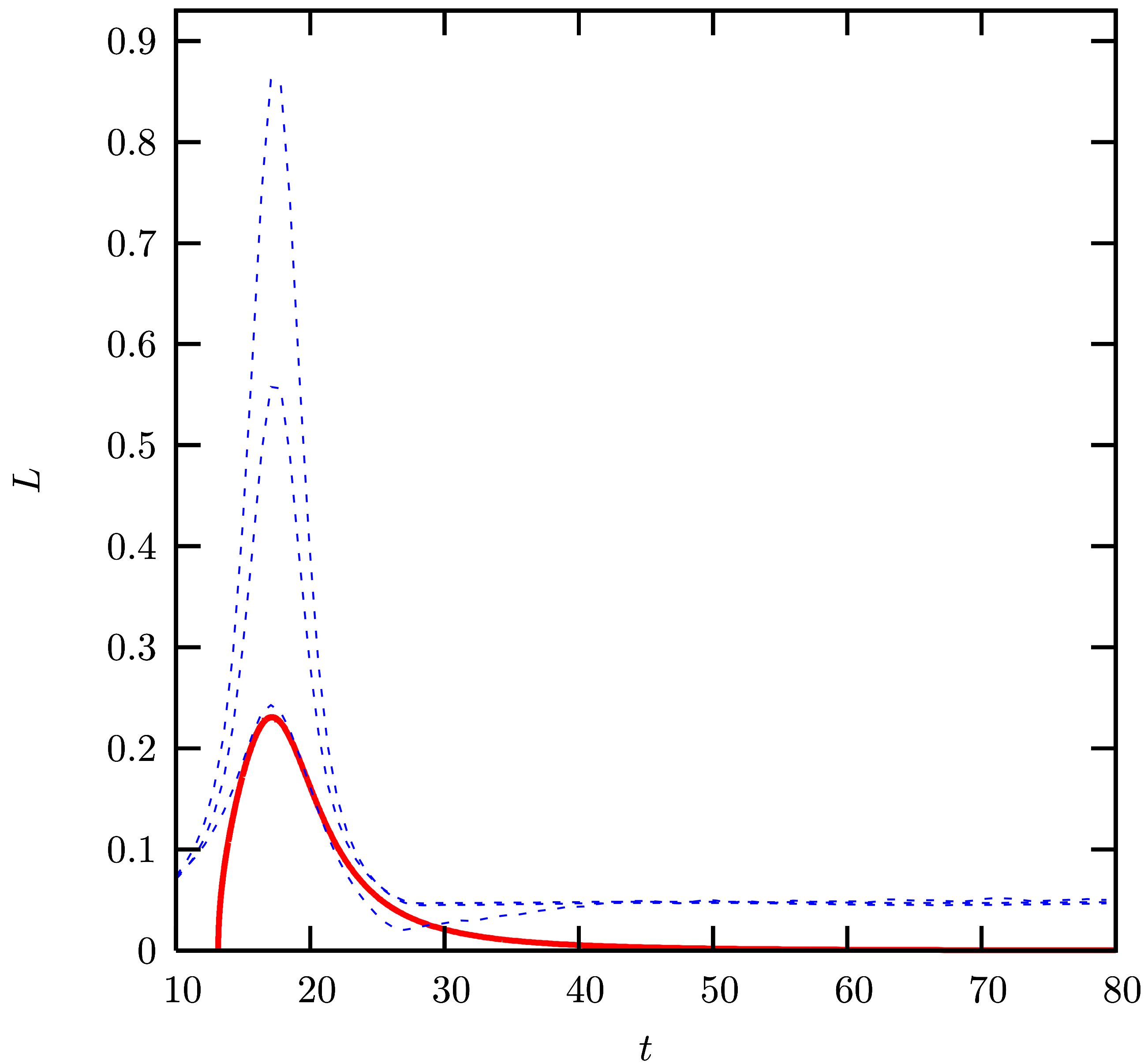
12 Numerical comparison

- ☆ $\dot{n} = 1$ & $v(t)$ as analytic case.
- ☆ Only a flash of luminosity, $\Rightarrow$ $v(t > 2\pi, x = 0) = 0$.
- ☆ Initial conditions: $v(t = 0, x) = 0.9$, $p(t = 0, x) = 0.001$, $n = \dot{n}/\gamma(t = 0, x)v(t = 0, x)$
- ☆ We also checked two more cases by using: $p \to \zeta p$ with $z = 0.1,\ 0.2$.
- ☆ Initial energy given by:

$$E_0 = \int_0^t \left[1 + \left(3 + v^2\right) \frac{1}{n} \frac{\mathrm{d}p}{\mathrm{d}t} - \left(3 + v^2\right) \frac{p}{n^2}\right] \gamma \mathrm{d}t, \tag{15}$$

- ☆ Once the shockwaves are captured, the energy between them is given by:

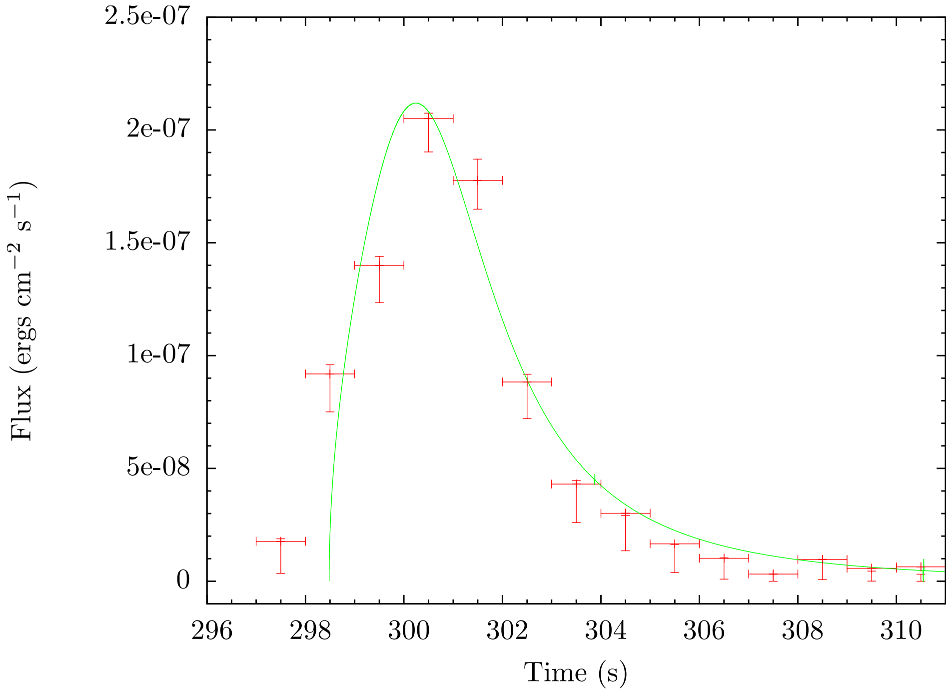
$$E_{\mathrm{ws}} = \sum n\gamma\Delta x + \sum p\gamma \left(3 + v^2\right) \Delta x. \tag{16}$$

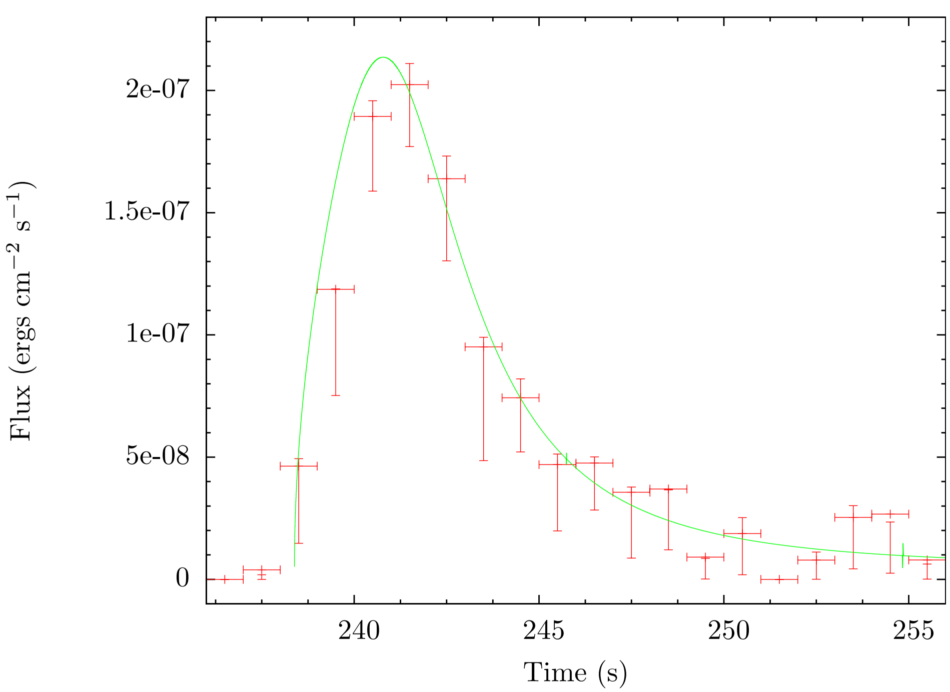


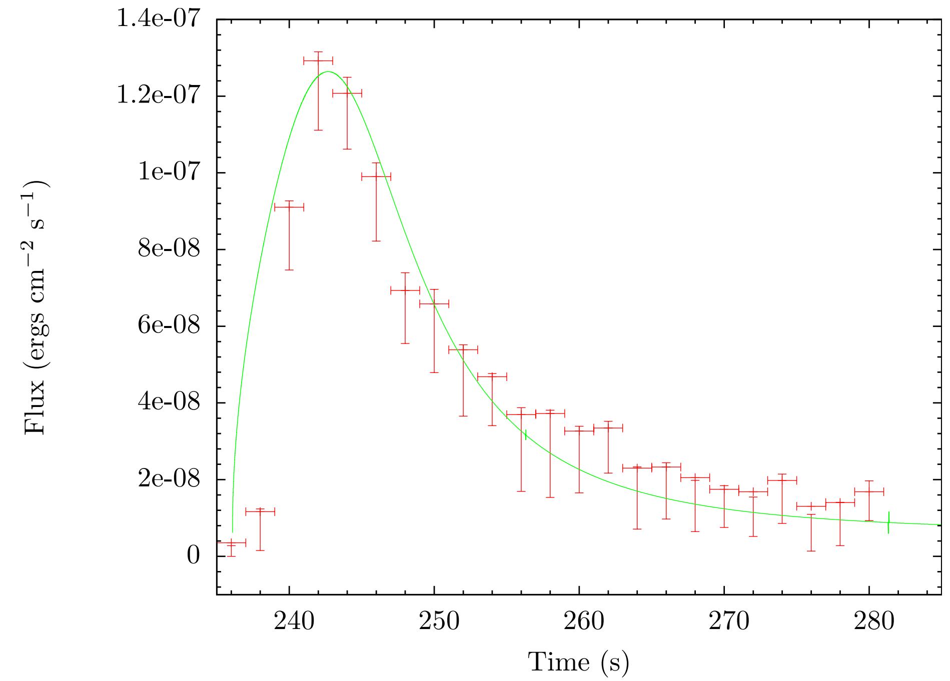
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
L
10
20
30
40
50
60
70
80
t

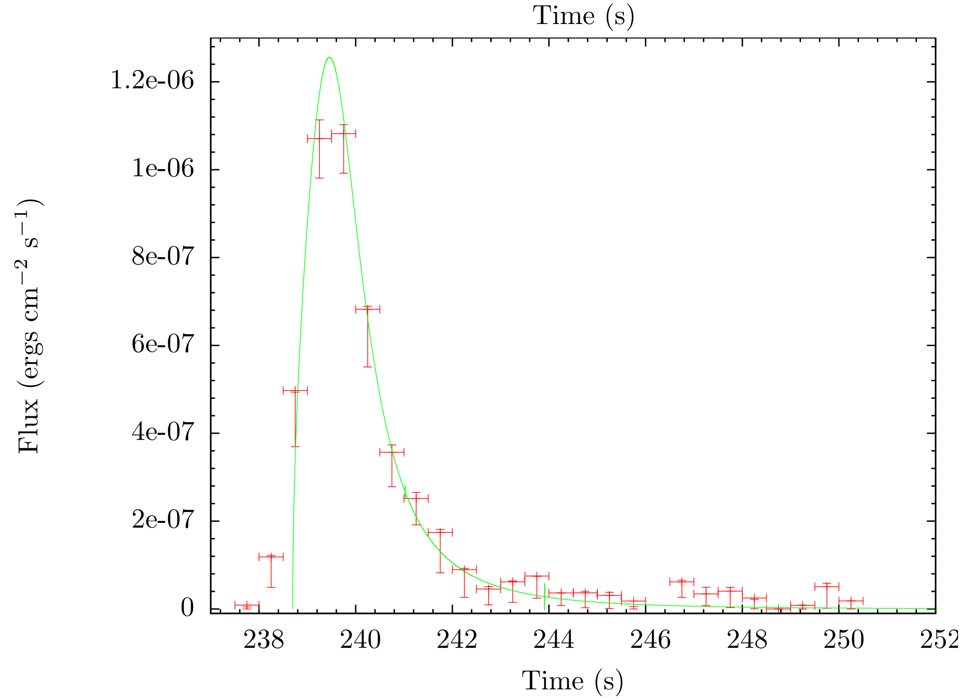
13 Light curves (Mendoza et al. 2009)

- We used 5 long GRBs with simple light curves.
- Fluxes and times are observed.
- Fits are obtained using a simple sinusoidal velocity.
- Linear adjustment to the observed data implies knowing $\dot{m}$ and w for each GRB.



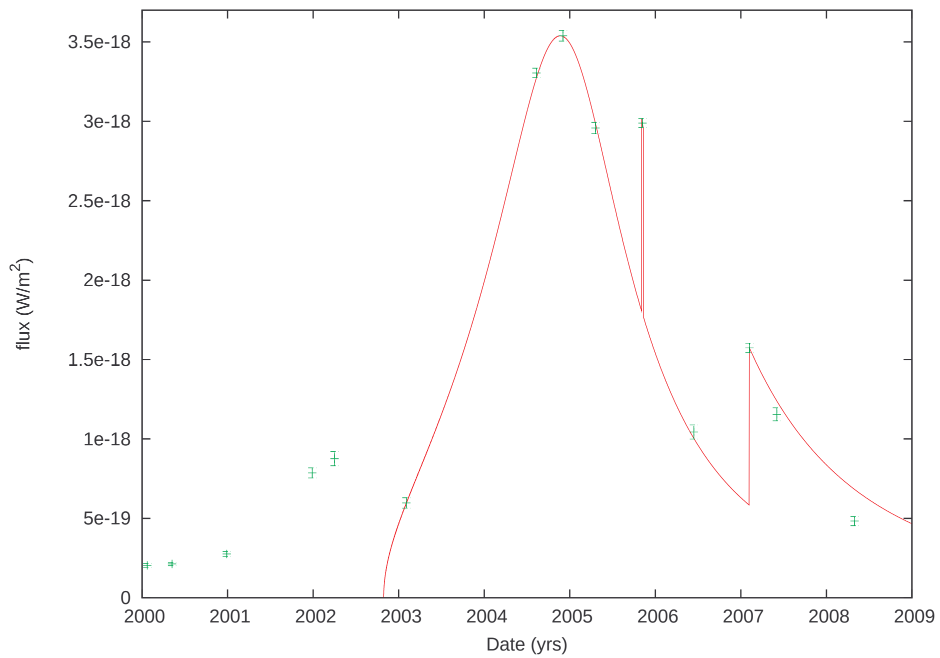



Flux (ergs cm^{-2} s^{-1})
1.4e-07
1.2e-07
1e-07
8e-08
6e-08
4e-08
2e-08
0
240
250
260
270
280
Time (s)

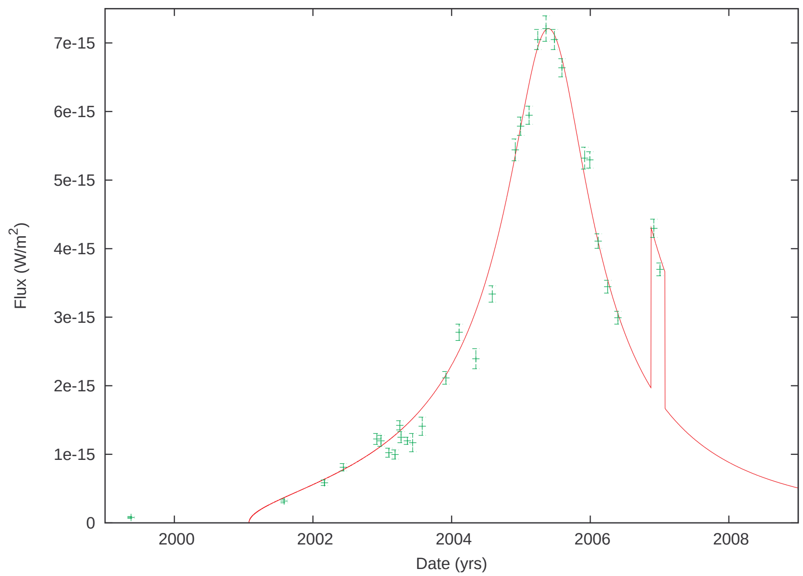

Flux (ergs cm^{-2} s^{-1})
1.2e-06
1e-06
8e-07
6e-07
4e-07
2e-07
0
238
240
242
244
246
248
250
252
Time (s)

14 M87-HST1 knot

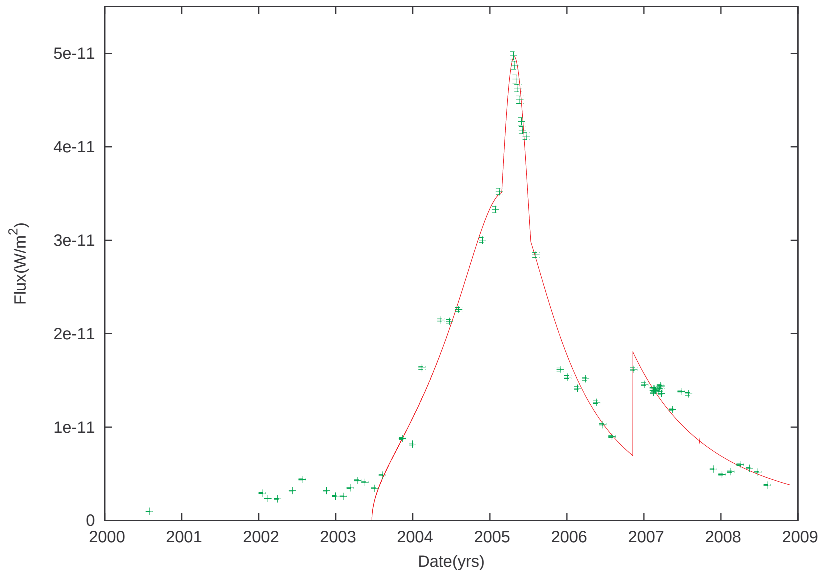
- Shows apparent superluminal motion.
- Light curves have been produced recently in radio, UV & X (Harris 2003, 2006, 2009, Madrid 2009, Chang et al. 2010, Chung et al. 2010, Perlman 2003, Wates 05).
- Fit observations of HST1 with our model (Coronado & Mendoza 2010).



HST1 in radio



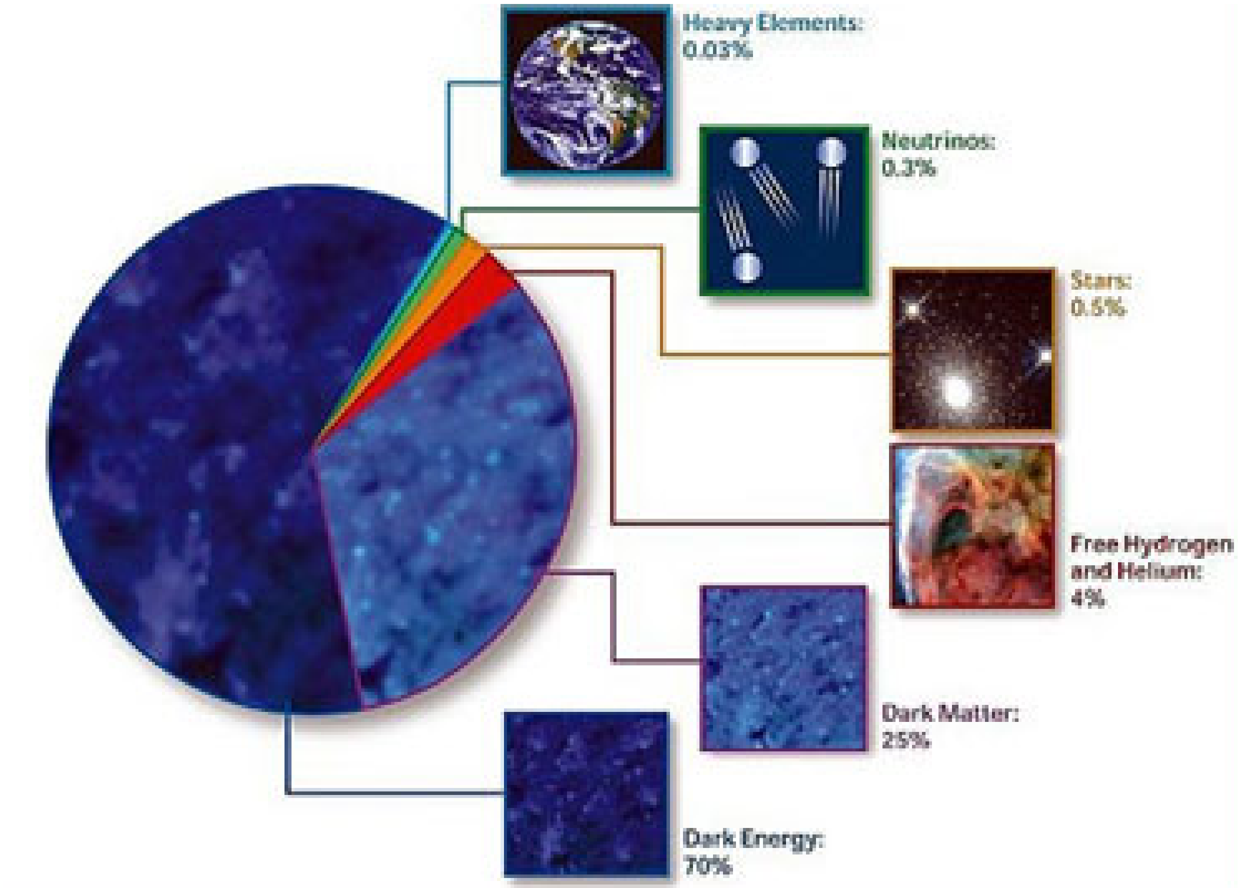
HST1 in UV



HST1 in X

15 Observational cosmology with long GRBs?

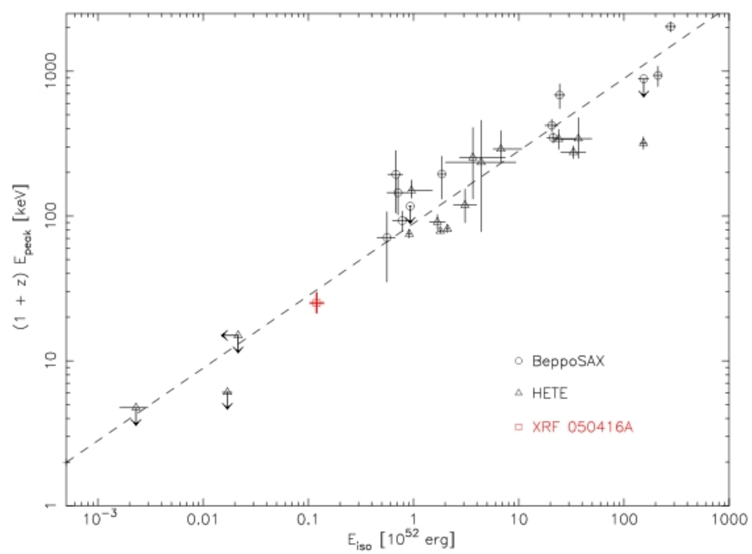
☆ Since 1998 a revolution on cosmology became possible using observations of SNIa since they can be thought of as "standard candles": dark energy appeared on the cosmography chart.



- ☆ One of the big challenges of observational modern cosmology is to find the values of the energy density parameters:

$$\Omega_{\rm tot} = \Omega_{\rm matt} + \Omega_{\rm DM} + \Omega_{\rm rad} + \Omega\kappa + \Omega_{\Lambda} = 1.$$

- ☆ Main problem to extend the Hubble diagram! Note that we can't use GRBs in principle since they are not standard candles at all!
- ☆ $E_{\rm peak} - E_{\rm iso}$ Amati (2002) empirical relation.
- ☆ Ghirlanda, Ghisellini, Firmani ... 2008, 2009, 2010 have reproduced Hubble diagrams using empirical relations
- ☆ Result: *concordance model* is coherent with their fits at $z \lesssim 4.5$.



- ☆ Note that GRBs and SNIa should not be considered to be competing standard candles but as complementary cosmological probes in two distinct redshift domains (Firmani et al 2007).
- ☆ All empirical relations are just EMPIRICAL. They essentially lack of a model.
- ☆ We are using Mendoza et al. (2009) model in order to build a Hubble diagram D_L vs z at large redshifts ($z \gtrsim 1.4$).
- ☆ For our model $L = L(\Gamma, \dot{m}, \omega, \Delta\Gamma)$, with:

$$\Gamma \sim 10 - 500, \qquad \dot{m} \sim 1\,\mathrm{M}_\odot\,\mathrm{s}^{-1}, \qquad \omega^{-1} \sim 10\,\mathrm{s}$$

- ☆ We obtain statistical distributions for $\dot{m}$ and ω for all known GRBs with $z \lesssim 1.4$. With these, observing a GRB with $z \gtrsim 1.4$ we assign it a $\dot{m}$ and ω and using $L = F/4\pi D_\mathrm{L}^2$, we build the Hubble diagram D_L vs z.

16 Concluding remarks & work in progress

- ☆ Shock waves appear on astrophysical flows since many are supersonic. High relativistic accretion/ejection flows appear since the dynamics of flows occur about a high relativistic central objects (e.g. black hole).
- ☆ We have built a simple to use model to understand the light curves of relativistic working surfaces in jets associated to long GRBs, quasars and micro-qsrs.
- ☆ Empirical correlations on the observed features of GRBs might all be wrong, particularly if they show an evolution with redshift. Worst of all, they don't have any model to rely on.
- ☆ Using our model, we are building now a Hubble diagram which can be extended up to $z \sim 8$. This will show the most extended probe of our universe's geometry and its evolution at the non-CMBR level (stay tuned for coming results).

Talk available at http://www.mendozza.org/sergio/talks.