HPC PROJECTS IN ASTROPHYSICS AT INAF/OAPA: CURRENT CHALLENGES AND FUTURE PERSPECTIVES

Salvatore Orlando

INAF - Osservatorio Astronomico di Palermo, Italy

The group at INAF/OAPa

INAF – Osservatorio Astronomico di Palermo

- Salvatore Orlando
- Marco Miceli
- Fabrizio Bocchino
- Flavio Morale (CED)
- Salvo Speziale (CED)

Dip. di Fisica e Chimica, Università di Palermo

- Fabio Reale
- Giovanni Peres
- Sara Bonito

PhD and undergratuate students of the Univ. of Palermo

- Antonino Petralia (PhD thesis)
- Enrico Barbera (PhD thesis)
- Guglielmo Costa (master thesis)

Active Research Lines

- **Solar Physics** (PRACE project; PI F. Reale)
  - Dynamics of magnetic structures;
  - Evolution of flares;
  - Coronal heating mechanism(s);

- **Young stellar objects** (ISCRA Class A; PI S. Orlando)
  - Mass accretion processes;
  - Effects of coronal activity on the disk stability;
  - Protostellar jets;

- **Pyisics of shocks propagating through inhomogeneous media** (PRACE project; PI S. Orlando)
  - Interaction of SNRs with the surrounding environment;
  - Physical and chemical evolution of ejecta in SNRs;
  - Effects of cosmic rays acceleration in SNRs;
  - Hydrodynamic modeling of nova outbursts;

Hydrodynamic and MHD modeling

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \,,$$

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u} - \boldsymbol{B}\boldsymbol{B} + \boldsymbol{I}P_t - \boldsymbol{\tau}) = \rho \boldsymbol{g} \,,$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot [\boldsymbol{u}(\rho E + P_t) - \boldsymbol{B}(\boldsymbol{u} \cdot \boldsymbol{B}) - \boldsymbol{u} \cdot \boldsymbol{\tau}] = \rho \boldsymbol{u} \cdot \boldsymbol{g} - \nabla \cdot \boldsymbol{F}_{\mathrm{c}} - n_{\mathrm{e}} n_{\mathrm{H}} \Lambda(T) + Q(R, \theta, \phi) \,,$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \cdot (\boldsymbol{u}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{u}) = 0 \,,$$

where

$$P_t = P + \frac{\boldsymbol{B} \cdot \boldsymbol{B}}{2} \,, \qquad E = \epsilon + \frac{\boldsymbol{u} \cdot \boldsymbol{u}}{2} + \frac{\boldsymbol{B} \cdot \boldsymbol{B}}{2\rho} \,,$$

THE TOOLS

NUMERICAL CODES

FLASH (Fryxell+ 2000)
Univ. of Chicago, USA

PLUTO (Mignone+ 2007)
Univ. of Turin, Italy

HPC FACILITIES

- CINECA (Italy)
- BSC (Spain)
- CINES (France)
- SCAN (INAF/OAPA)
- COMETA (Italy)

Coronal Heating

(PRACE n° 2011050755)
The way to heating the solar corona: finely-resolved twisting of magnetic loops

PI: F. Reale
Co-I: S. Orlando, M. Miceli, M. Guarrasi, A. Mignone

Simulations: 3D MHD (resistivity; therm. cond.; rad. cool.; grav.)

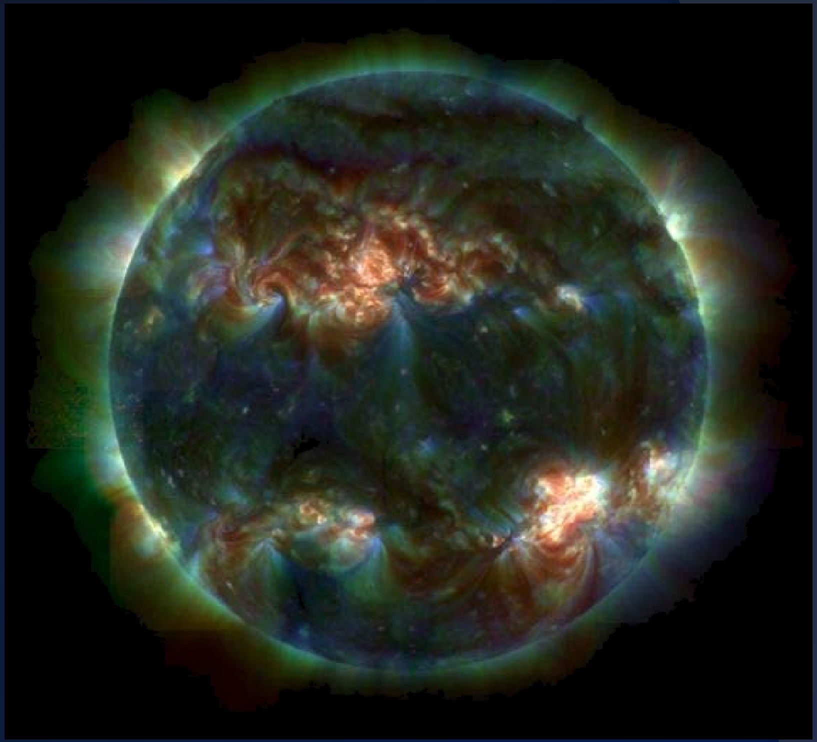
code: PLUTO 4 (Mignone et al. 2007)

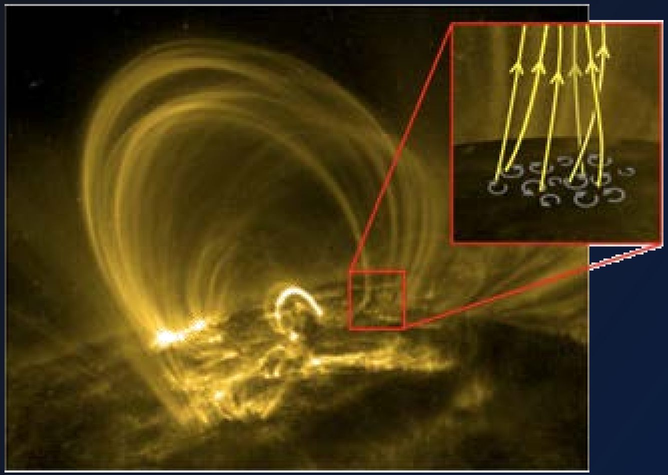
Resources: ~ 31 Mhours on FERMI (CINECA)
(storage ~ 10 TB)

Coronal Heating

The question of what heats the solar and stellar coronae to million degrees remains a compelling problem in Astrophysics

The source of coronal heating is believed to be the photospheric plasma motions carried to the corona by the magnetic field that also confines plasma in coronal loops





The question is how the magnetic energy is converted into heat that powers the loops

Coronal Heating

The energy may be obtained from the progressive stressing of the magnetic field lines driven by the motion of the photospheric granulation

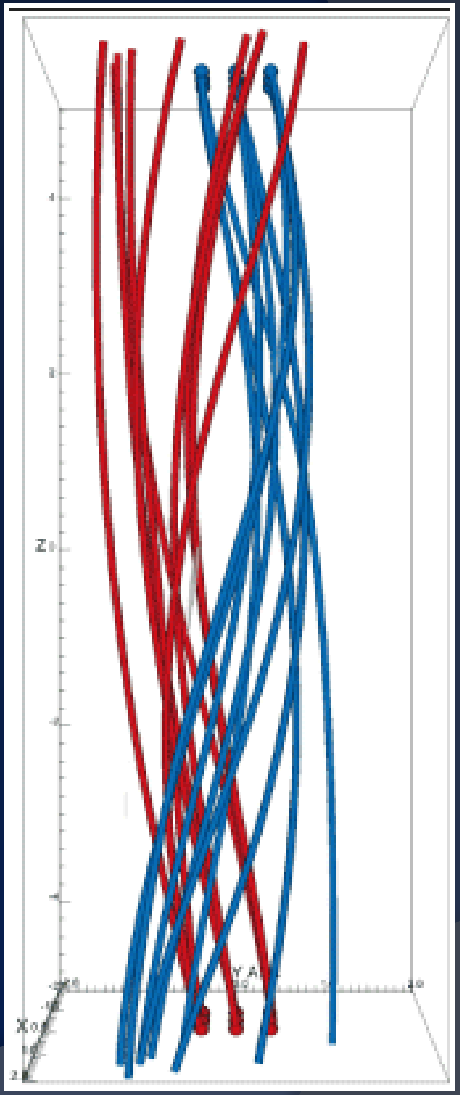
Above a certain threshold the magnetic field lines reconnect into less stressed configurations

In our scenario, the magnetic field is stressed by the progressive twisting due to the rotation of the loop footpoints (Golub et al. 1980)

GOAL:

study the twisting of coronal loops with unprecedented model completeness and resolution, necessary to answer reliably important questions, never addressed or feasible before

where does reconnection occur along the loop?
Does it reach a steady-state rate?



The 3D MHD model

Three-dimensional cylindrical coordinates

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 ,$$

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u} - \boldsymbol{B}\boldsymbol{B} + \boldsymbol{I} P_t) = \rho \boldsymbol{g} ,$$

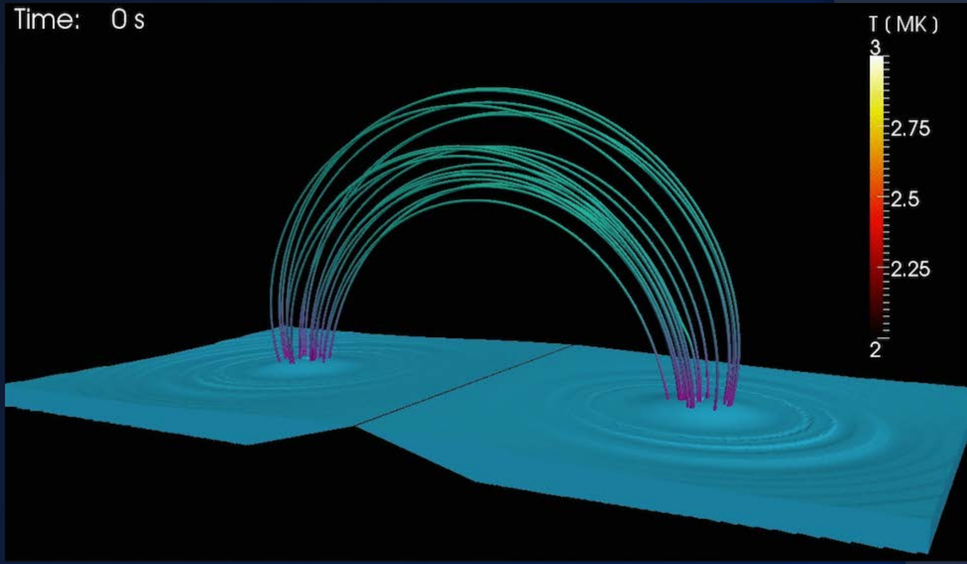
$$\frac{\partial \rho E}{\partial t} + \nabla \cdot [\boldsymbol{u}(\rho E + P_t) - \boldsymbol{B}(\boldsymbol{u} \cdot \boldsymbol{B})] =$$

$$- \nabla \cdot [(\eta \cdot \boldsymbol{J}) \times \boldsymbol{B}] + \rho \boldsymbol{u} \cdot \boldsymbol{g} - \nabla \cdot \boldsymbol{F}_{\rm c} - n_{\rm e} n_{\rm H} \Lambda(T)$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \cdot (\boldsymbol{u}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{u}) = -\nabla \times (\eta \cdot \boldsymbol{J}) ,$$

where

$$P_t = P + \frac{\boldsymbol{B} \cdot \boldsymbol{B}}{2} , \qquad E = \epsilon + \frac{\boldsymbol{u} \cdot \boldsymbol{u}}{2} + \frac{\boldsymbol{B} \cdot \boldsymbol{B}}{2\rho} ,$$



Simulations performed with the PLUTO code (Mignone et al. 2007)

LOOP initial conditions

$L = 2.5e9$ cm

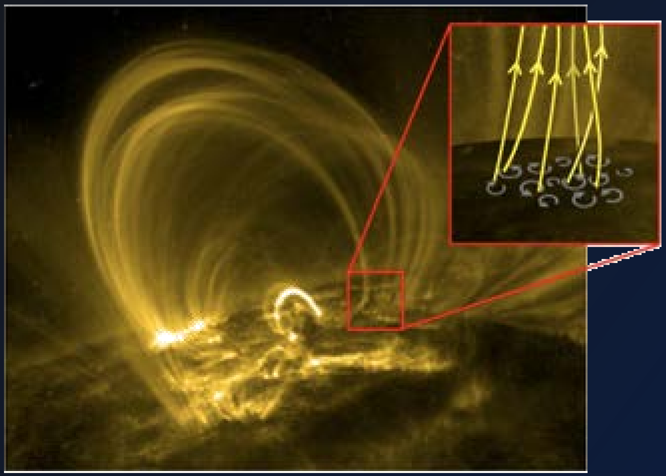
$T_0 = 7e5$ K

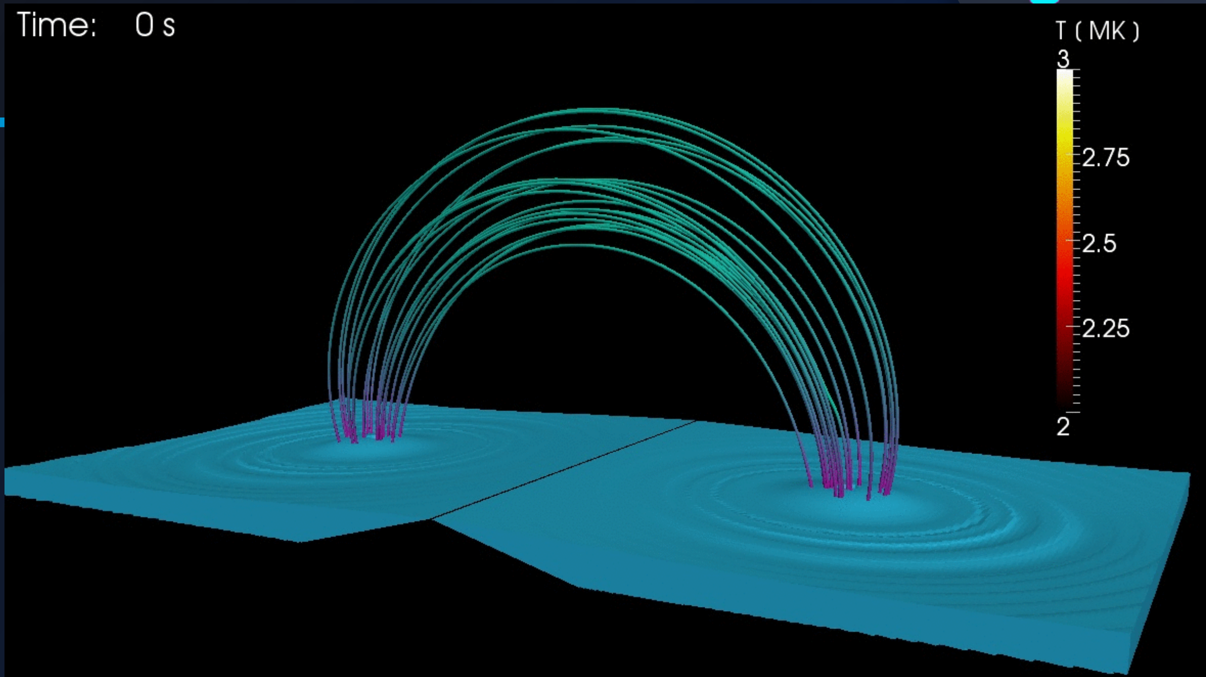
$n_0 = 1e8\ \mathrm{cm}^{-3}$

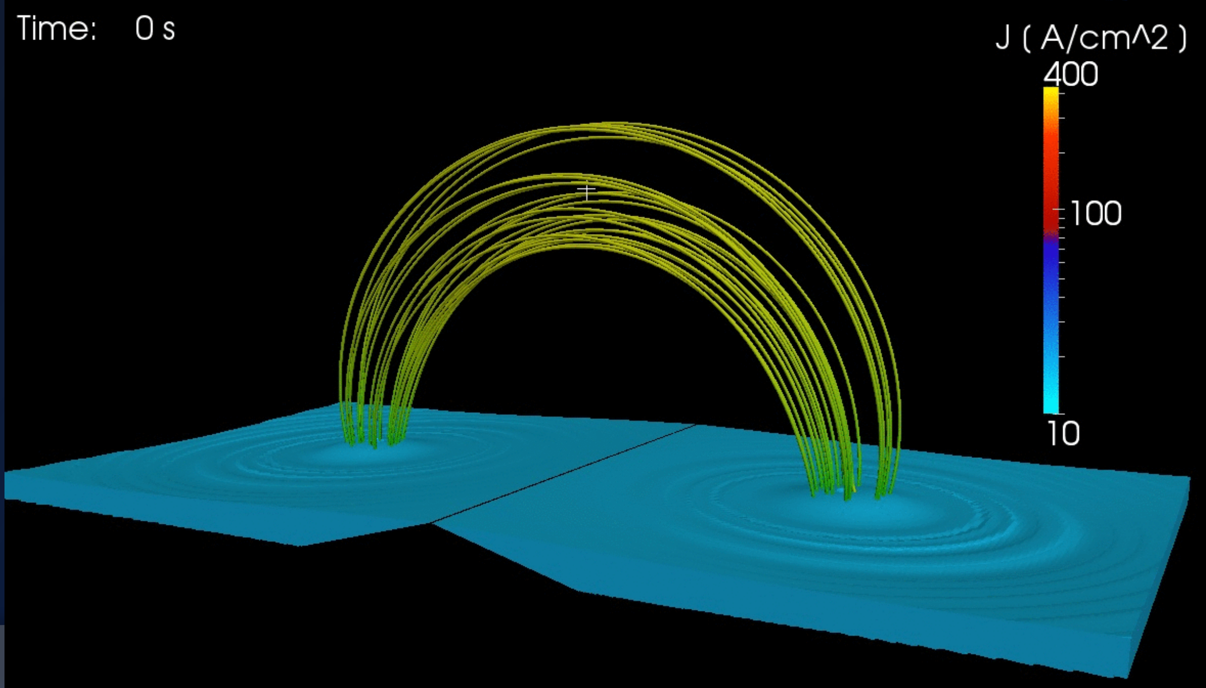
Coronal Heating

Twist of B
- J along the axis
- Heating of plasma
- Chromospheric
  evaporation

V_t = 5 km/sec







YSOs: star-disk interaction, flares

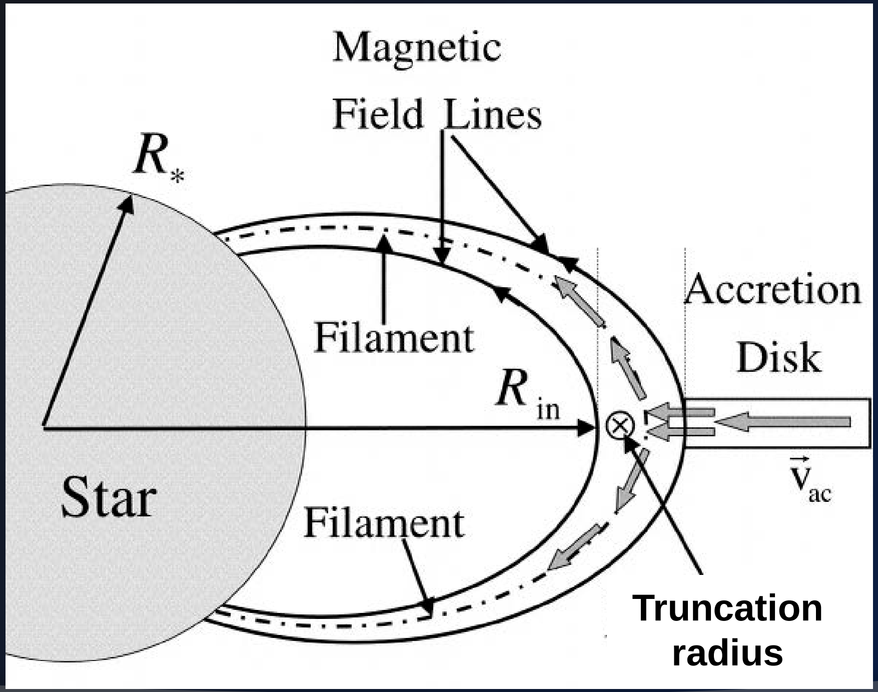
MACFLYS (ISCRA Class A HP10A4ZCV5)
Mass accretion onto young stellar objects driven by flaring activity in protostellar disks

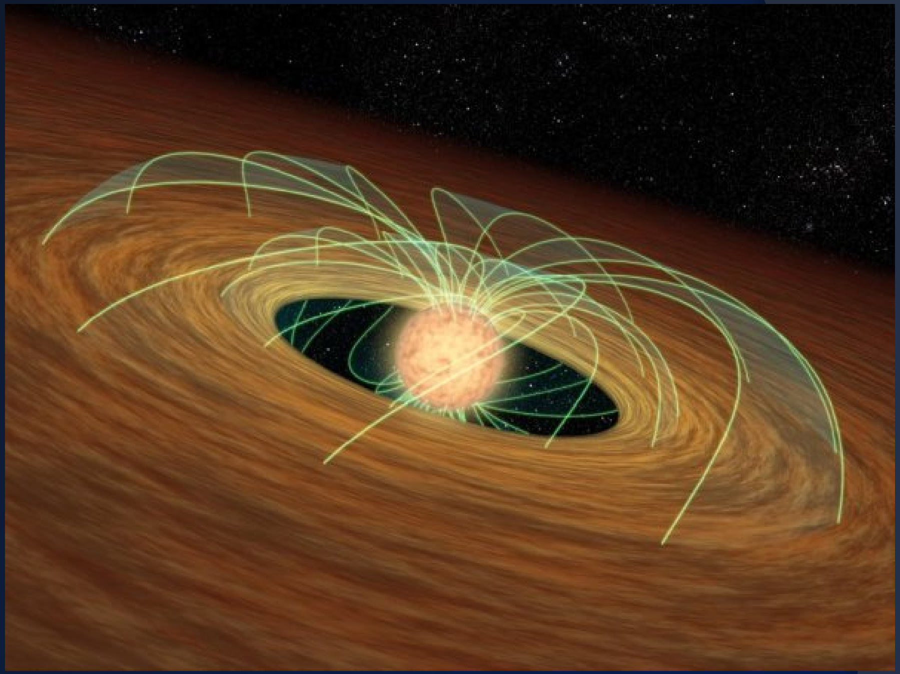
PI:	S. Orlando
Co-I:	F. Reale, G. Peres, A. Mignone
Simulations:	3D MHD (therm. cond.; rad. cool.; grav.; visc.; heat.)
code:	PLUTO 3.1.1 (Mignone et al. 2007)
Resources:	> 1 Mhours on IBM/Sp6 (CINECA) ~ 3 Mhours on FERMI (CINECA) 512 – 8000 cores (storage ~ 1 TB)

The magnetospheric accretion scenario

Young low-mass stars are surrounded by circumstellar disks with which they interact in a complex fashion, with accretion of mass and ejection of collimated outflows

The accretion process is regulated by the stellar magnetic field





The magnetic field disrupts the inner part of the disk at a distance of a few stellar radii (the truncation radius) and guides the disk's material toward the central star (accretion)

The 3D MHD model

Three-dimensional spherical coordinates

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0\,,$$

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u} - \boldsymbol{B}\boldsymbol{B} + \boldsymbol{I}P_t - \boldsymbol{\tau}) = \rho \boldsymbol{g}\,,$$

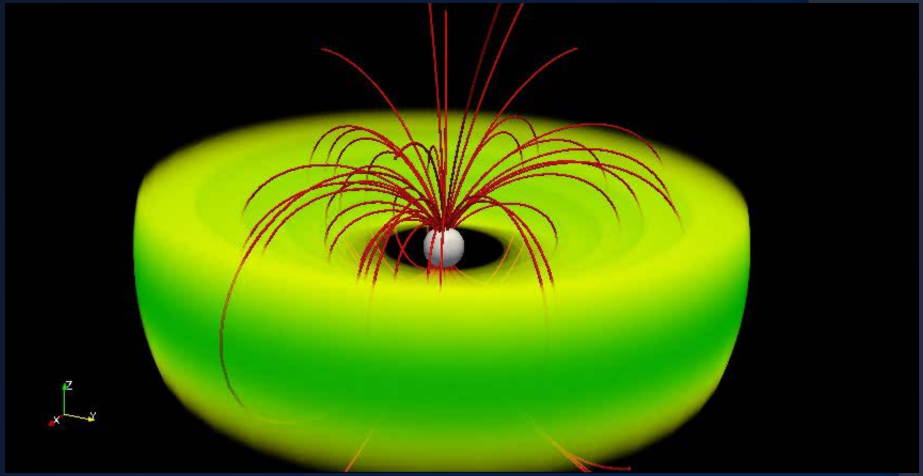
$$\frac{\partial \rho E}{\partial t} + \nabla \cdot [\boldsymbol{u}(\rho E + P_t) - \boldsymbol{B}(\boldsymbol{u}\cdot\boldsymbol{B}) - \boldsymbol{u}\cdot\boldsymbol{\tau}] = \rho \boldsymbol{u}\cdot\boldsymbol{g} - \nabla\cdot\boldsymbol{F}_{\rm c} - n_{\rm e}n_{\rm H}\Lambda(T) + Q(R,\theta,\phi)\,,$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \cdot (\boldsymbol{u}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{u}) = 0\,,$$

where

$$P_t = P + \frac{\boldsymbol{B}\cdot\boldsymbol{B}}{2}\,, \qquad E = \epsilon + \frac{\boldsymbol{u}\cdot\boldsymbol{u}}{2} + \frac{\boldsymbol{B}\cdot\boldsymbol{B}}{2\rho}\,,$$

Disk's viscosity:
Shakura-Sunyaev α-model



Simulations performed with the PLUTO code (Mignone et al. 2007)

CTTS

$M_* = 0.8\ M_{sun}$ $R_* = 2\ R_{sun}$ $B_* \sim 1$ kG

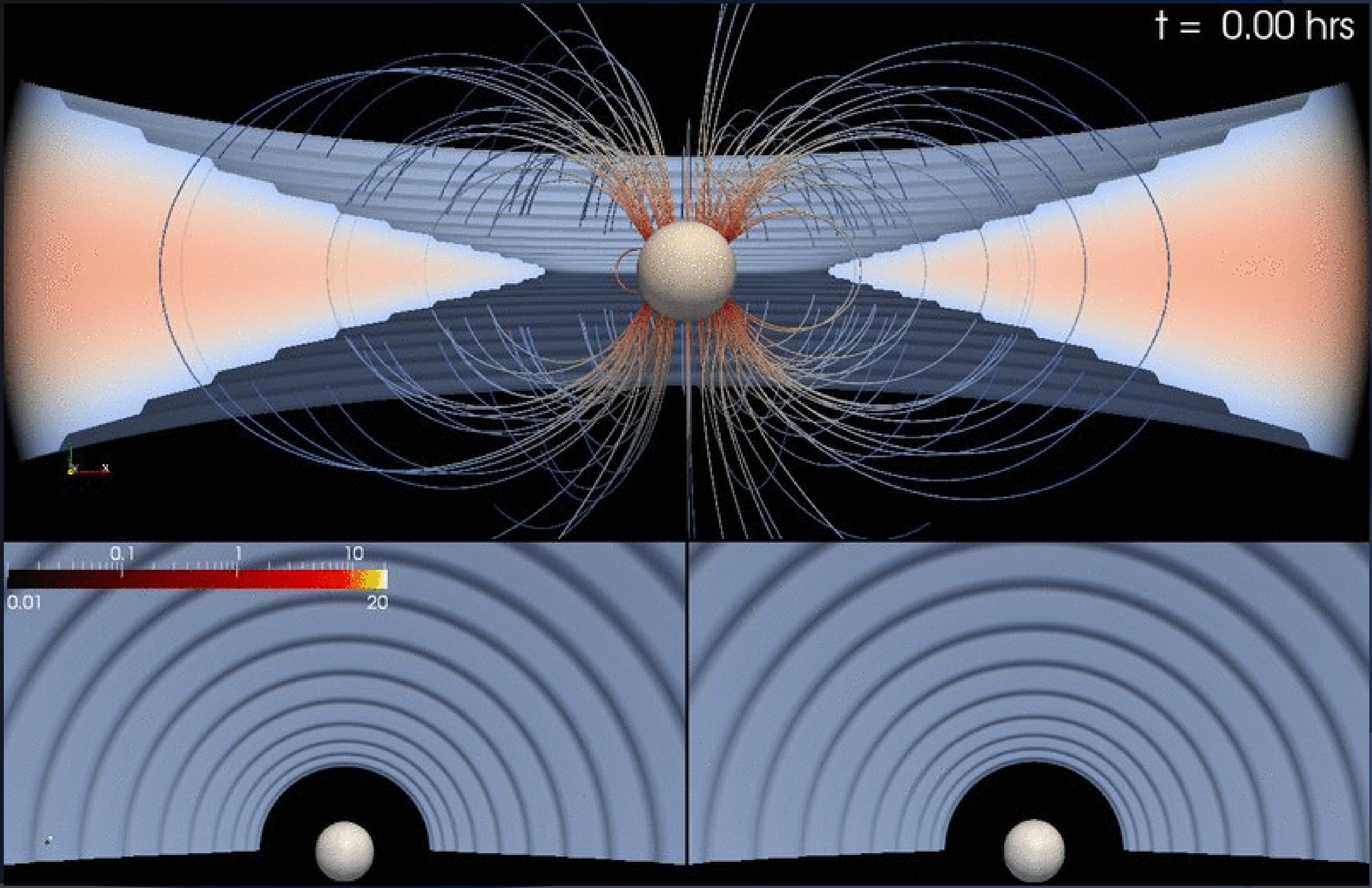
Disk

$R_d \sim 3\ R_*$ $R_{co} \sim 9\ R_*$

Flares

$R_{fl} \sim 3 - 6\ R_*$

YSOs: star-disk interaction, flares



Physical and chemical evolution of ejecta in SNRs

SN2SNR (PRACE n° 2012060993)
Filling the gap between supernova explosions and their remnants

PI: S. Orlando
Co-I: F. Bocchino, M. Miceli, M.L. Pumo, F. Reale, G. Peres

Simulations: 1D RHD + 3D MHD (cosmic ray acc. feedback)

Codes: general-relativistic, radiation hydrodynamics, Lagrangian code for SN (Pumo & Zampieri 2011), FLASH for SNR (Fryxell+ 2000)

Resources: ~ 3 Mhours on FERMI (CINECA)
~ 8 Mhours on MareNostrum III (BSC) (23 Mh on FERMI)
4000 – 8000 cores
(storage ~ 15 TB)

SN 1987A

The remnant of SN 1987A provides a unique opportunity to investigate the evolution of a SNR during the early phase of its evolution:

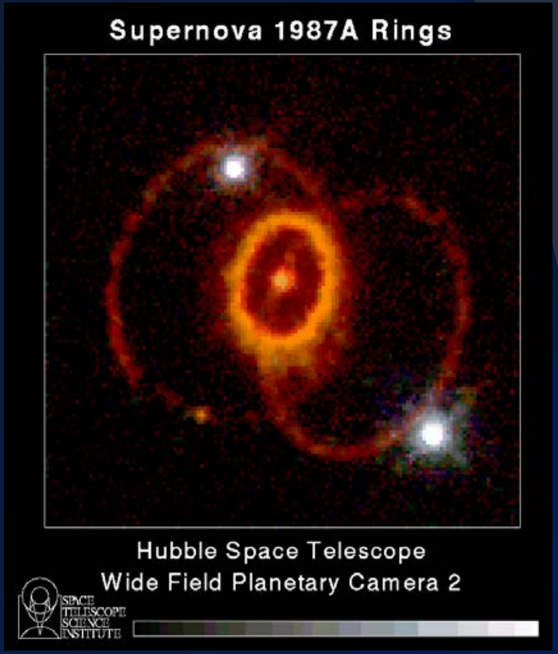
- Probe the structure of the CSM immediately surrounding the SN (clues on the final stages of the star' s evolution)

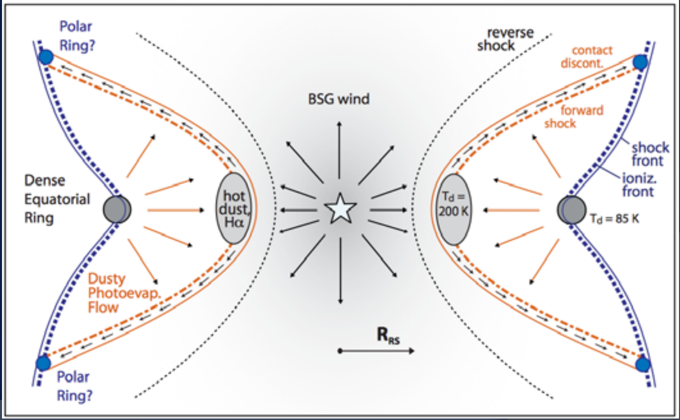
- Probe the structure of the ejecta
(clues on the dynamics of the SN explosion)

Origin of the observed structures

interaction of a wind from the slow red supergiant phase with the faster wind from the blue supergiant phase (e.g. Luo & McCray 1991).

Currently, the explosion is sweeping up the inner equatorial ring that was formed by the late stages of the star' s evolution.





Modeling the SNR evolution

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \ ,$$

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

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho E + P)\mathbf{u} = -n_{\rm e} n_{\rm H} \Lambda(T) \ ,$$

$$\text{where} \qquad E = \epsilon + \frac{1}{2}|\mathbf{u}|^2 \ ,$$

- Clumping of ejecta (Orlando+ 2012)
- Radiative losses from optically thin plasma
- Non-equilibrium of ionization
  - time evolution of each parcel of gas is followed (Dwarkadas+ 2010)
  - deviations from equilibrium of selected elements (O, Ne, Mg, Si) is calculated
- Tracers to follow the evolution of ejecta, HII region, and ring material

Initial conditions

20 hours after the SN explosion

Spatial resolution

A major challange was capturing the enormous range in spatial scales
- Initial remnant radius ~ 20 AU (3e14 cm)
- Full spatial domain ~ 1 pc (3e18 cm)

18 nested levels of adaptive mesh refinement
→ effective resolution ~ 0.2 AU (3e12 cm)

> 100 cells per remnant radius during the whole evolution

Equivalent uniform grid ~ 1e6 X 1e6 X 1e6

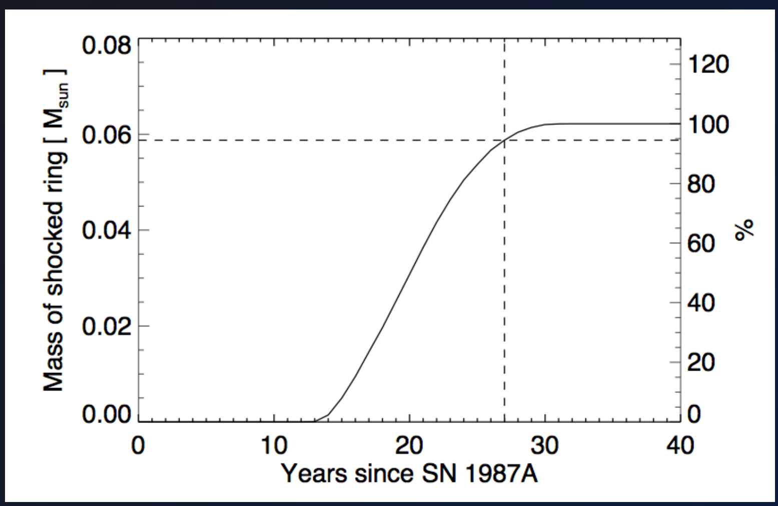
The evolution of SN 1987A

Our model

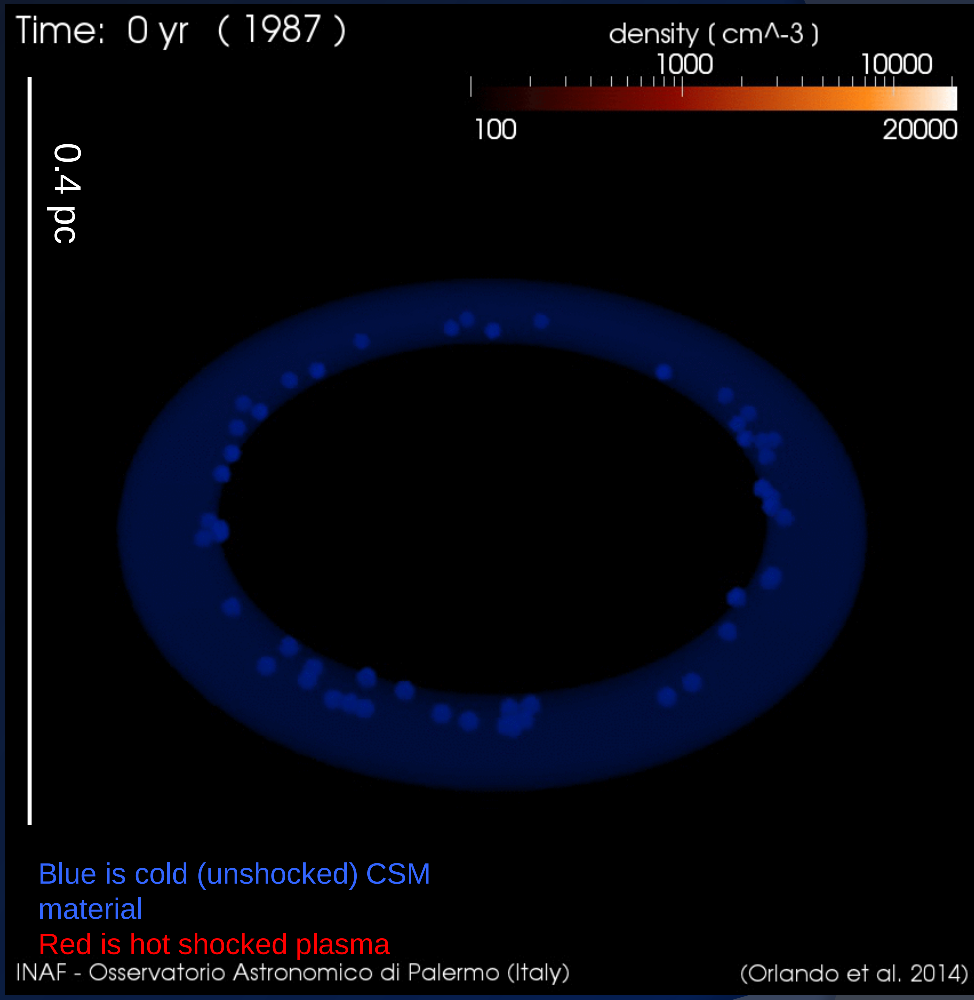
$M_{rg} \sim 0.062\ M_{sun}$
$\sim 0.040\ M_{sun}$ @ $n = 10^3\ cm^{-3}$
$\sim 0.022\ M_{sun}$ @ $n \sim 2.5 \times 10^4\ cm^{-3}$

Density structure of ionized gas of the ring from optical spectroscopic data (Mattila+ 2010)

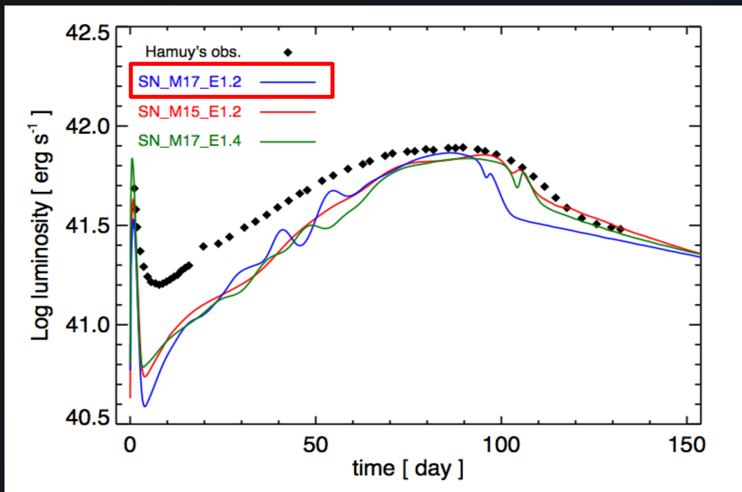
$M_{rg} \sim 0.058\ M_{sun}$
$\sim 0.046\ M_{sun}$ @ $n \sim 10^3\ cm^{-3}$ and $n \sim 3 \times 10^3\ cm^{-3}$
$\sim 0.012\ M_{sun}$ @ $n \sim 3 \times 10^4\ cm^{-3}$



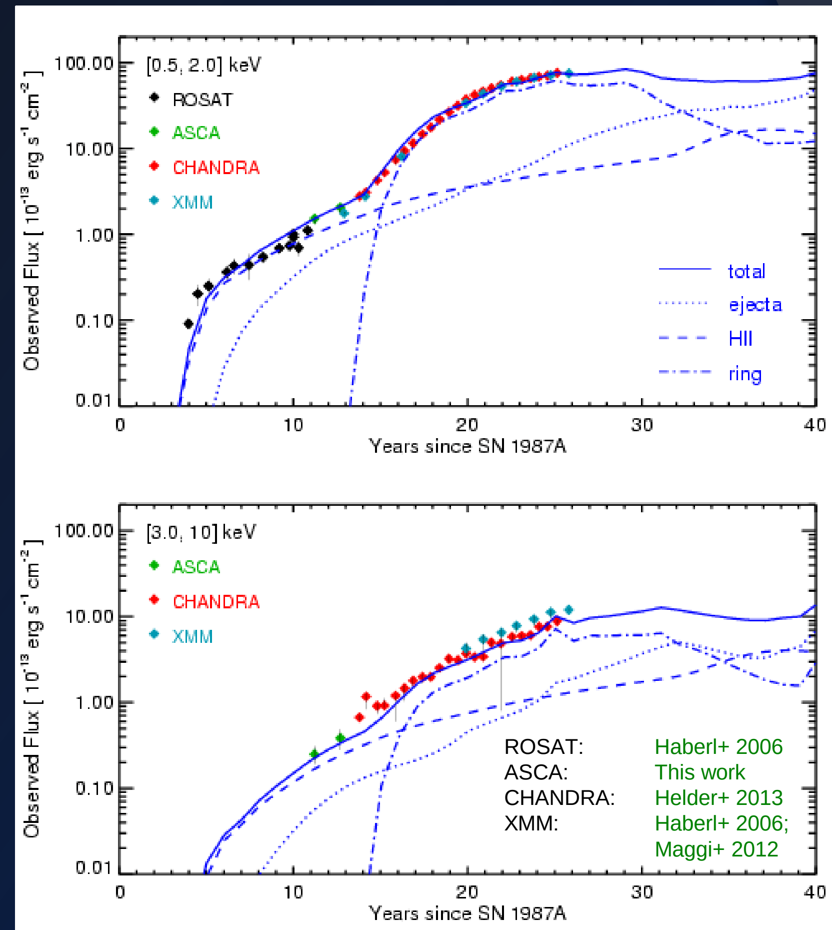
~ 95% of the ring material has been shocked at the current time (2014)



Lightcurves



Bolometric lightcurves of the SN models compared to that observed (Hamuy+ 1988)

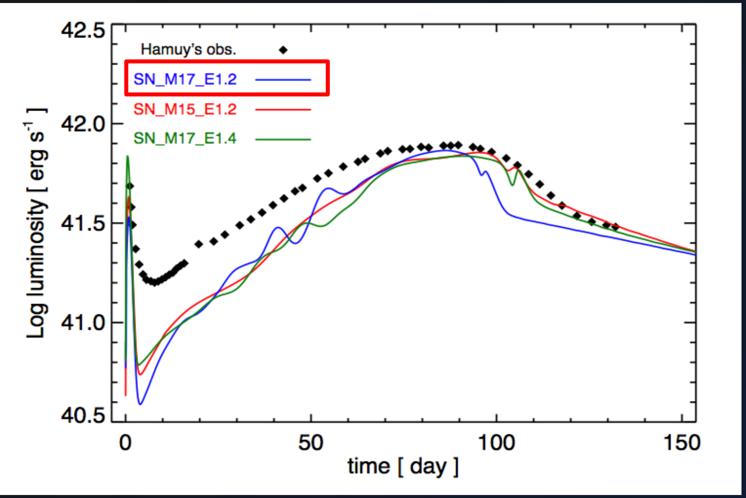


Abundances from Zhekov+ (2009)

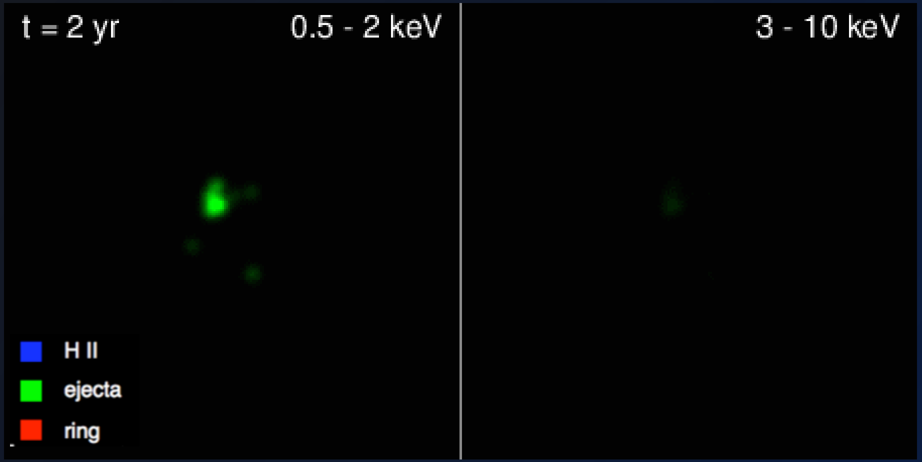
ISM Absorption: 2.35e21 cm^{-2} (Park+ 2006)

Distance: 51.4 kpc (Panagia 1999)

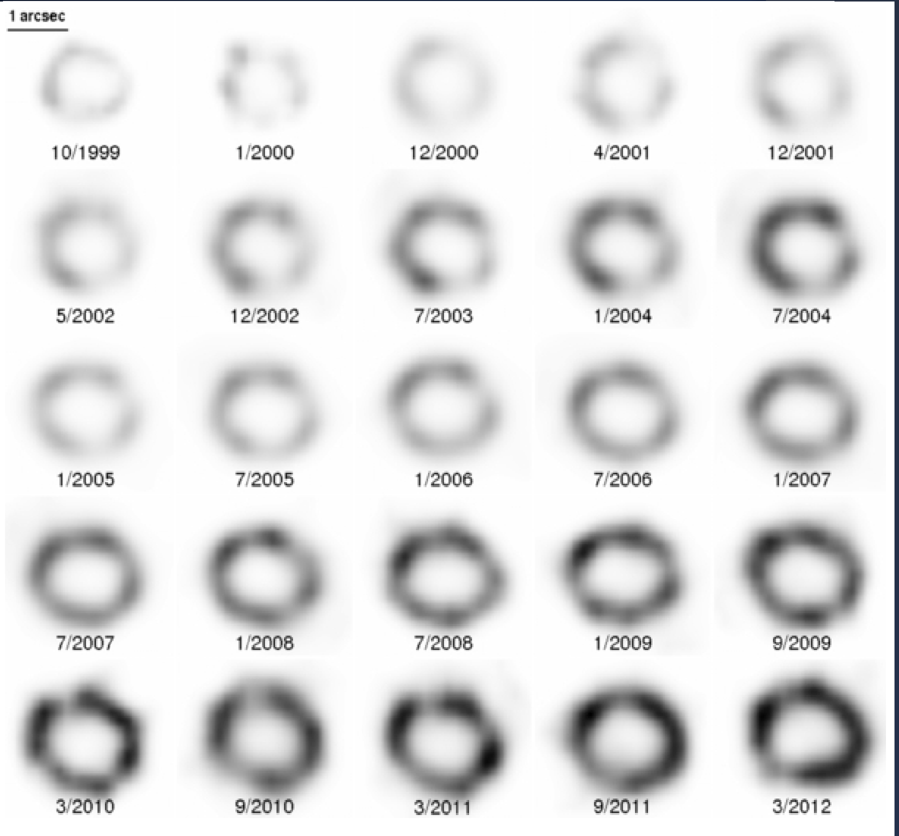
Lightcurves



Bolometric lightcurves of the SN models compared to that observed (Hamuy+ 1988)



Each image is normalized to its maximum



CHANDRA Observations (Helder+ 2012)

Abundances from Zhekov+ (2009)

ISM Absorption: 2.35e21 cm^{-2} (Park+ 2006)

Distance: 51.4 kpc (Panagia 1999)

Future Prospects

- Twisting of magnetic loops:
  investigate the relaxation of braided magnetic loops in order to find out how the braiding via footpoint motions determines the loop heating

  3D resistive MHD simulations including anomalous resistivity, thermal conduction, radiative losses, gravity, and an accurate description of the chromosphere

- Star-disk interaction in YSOs:
  study the impact of a violent CME originating from the protostar on the inner portion of the disk in order to investigate its effects on the disk stability

  3D MHD simulations including thermal conduction, radiative losses, gravity, heating, disk viscosity

- Dynamics of ejecta in SNRs:
  investigate the origin of metal rich mixed morphology (MM) SNRs and the role played by the interaction of the blast wave with the inhomogeneous CSM/ISM in determining the physical characteristics of MM SNRs

  3D MHD simulations including thermal conduction, radiative losses, NEI