MAGNETO-ROTATIONAL SUPERNOVA EXPLOSIONS: A COMPARISON BETWEEN STATE-OF-THE-ART NUMERICAL MODELS

Matteo Bugli[1,2] (MSCA fellow)

Collaborators: J.Guilet[2], K. Kotake[3], L. Kovalenko[4], B. Müller[5],
M. Obergaulinger[6], E. O'Connor[4], T. Takiwaki[7], V. Varma[8]

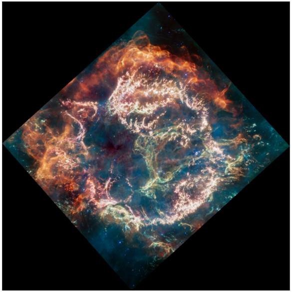
JOURNÉES SF2A - Marseille, 5th June 2024

1 2 3 4 5 6 7 8

Core-collapse Supernovae

- Gravitational collapse of a massive star (unstable iron core)
- Shock formation when nuclear densities are reached (stalling) ⇒ Proto Neutron Star
- Shock expansion and ejection of unbound material (explosion)

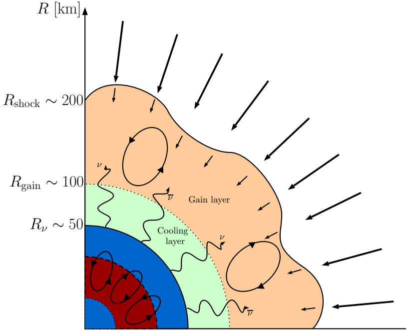
Credit: NASA, ESA, CSA



Where does the binding energy ($\sim 10^{53}$ erg) end up?

- Neutrino emission ($\sim$ 99%)
- Ejecta ($\sim$ 1%)
- Gravitational waves ($\sim 10^{-8}$)

Standard neutrino-driven CCSN



- PNS contraction ⇒ higher ν energies
- ν-cooling rate drops faster than ν-heating ⇒ Gain radius
- Energy deposition by ν_e and $\bar{\nu}_e$ absorption in gain layer
- Multi-D hydrodynamic instabilities aid the explosion (i.e. convection, SASI)

99% of core-collapse supernovae explode thanks to neutrinos

Outstanding explosions and magnetic fields

Explosion kinetic energy

- Typical supernova: 10^{51} erg
- Rare hypernovae and GRBs: 10^{52} erg

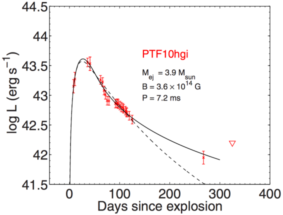
Total luminosity

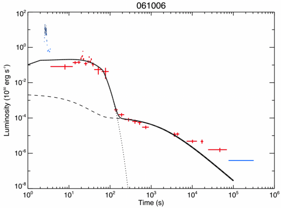
- Typical supernova: 10^{49} erg
- Superluminous SN: 10^{51} erg

Lightcurves and X-ray plateaus

- Strong dipolar magnetic field: $B \sim 10^{14} - 10^{15}$ G
- Fast rotation: $P \sim 1 - 10$ ms
- Kasen and Bildsten (2010); Dessart et al. (2012); Nicholl et al. (2013); Zhang and Mészáros (2001); Metzger et al. (2008); Lü et al. (2015); Gao et al. (2016)

Inserra et al. (2013)





Gompertz et al. (2014)

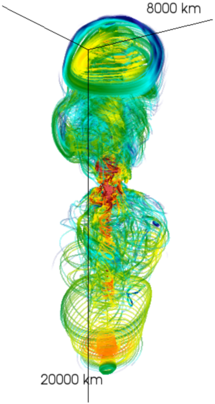
Magneto-rotational explosions

Core mechanism

- Rotation ⇒ energy reservoir
- Magnetic fields ⇒ means to extract that energy through magnetic stresses
- Powerful jet-driven explosions (Shibata et al., 2006; Burrows et al., 2007; Dessart et al., 2008; Takiwaki et al., 2009; Kuroda and Umeda, 2010; Winteler et al., 2012; Obergaulinger and á. Aloy, 2017)

Origin of the magnetic field

- Progenitor (Woosley and Heger, 2006; Aguilera-Dena et al., 2020)
- Stellar mergers (Schneider et al., 2019)
- PNS dynamos (Masada et al., 2015, 2022)



Obergaulinger and Aloy (2021)

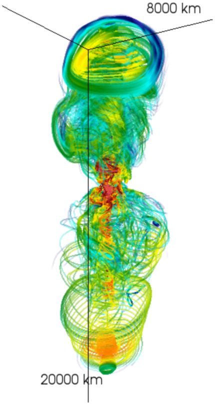
Magneto-rotational explosions

Core mechanism

- Rotation ⇒ energy reservoir
- Magnetic fields ⇒ means to extract that energy through magnetic stresses
- Powerful jet-driven explosions (Shibata et al., 2006; Burrows et al., 2007; Dessart et al., 2008; Takiwaki et al., 2009; Kuroda and Umeda, 2010; Winteler et al., 2012; Obergaulinger and á. Aloy, 2017)

Origin of the magnetic field

- Progenitor (Woosley and Heger, 2006; Aguilera-Dena et al., 2020)
- Stellar mergers (Schneider et al., 2019)
- PNS dynamos (Masada et al., 2015, 2022)



Obergaulinger and Aloy (2021)

Can different codes reproduce the same results?

The code comparison

The numerical codes

Code Name	Grid Geometry	Neutrinos	Dimensions
3DnSNe-IDSA (Takiwaki et al., 2016)	(r,θ,ϕ)	IDSA	2D, 3D
AENUS-ALCAR (Just et al., 2015)	(r,θ,ϕ)	M1	2D, 3D
CoCoNuT-FMT (Müller and Janka, 2015)	(r,θ,ϕ)	FMT	2D
FLASH-M1 (O'Connor and Couch, 2018)	(x,y,z)	M1	2D, 3D

Common settings

- Nuclear equation of state → SFHo (Steiner et al., 2013)
- Non-axisymmetric perturbation in density:

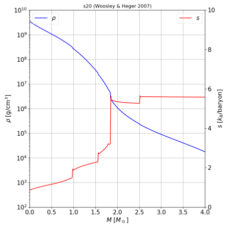
$$\delta\rho = \rho_0 \epsilon \sin(2\theta)\cos\phi \quad \text{with} \quad \epsilon = 0.01$$

- Spectral ν-transport schemes with 20 bins up to 300 MeV

The initial conditions

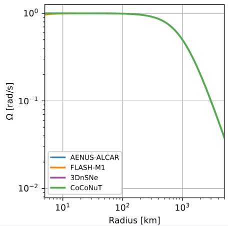
PROGENITOR

- s20: $M_{ZAMS} = 20 M_\odot$ with solar metallicity (Woosley and Heger, 2007)
- Iron core with mass $M_{\rm Fe} \simeq 1.85 M_\odot$ and radius $R_{\rm Fe} \simeq 2600$ km
- No rotation nor magnetic field from stellar evolution



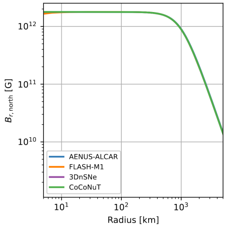
ROTATION RATE

- Inner core ($R_\Omega = 1000$ km) in solid body rotation ($\Omega_0 = 1$ rad/s)
- Constant specific angular momentum elsewhere with shellular differential rotation: $\Omega(r) = \Omega_0 \frac{R_\Omega^2}{R_\Omega^2 + r^2}$

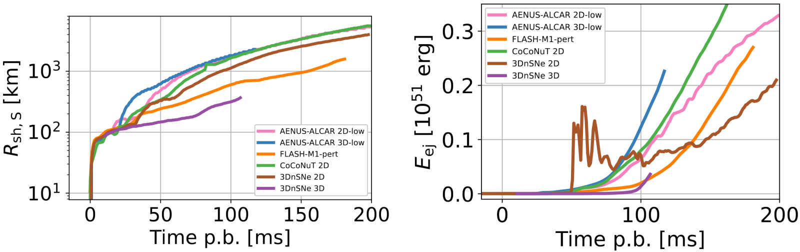


MAGNETIC FIELD

- Modified aligned dipole: constant intensity $B_0 \simeq 1.77 \times 10^{12}$ G within $R_0 = 1000$ km.
- Azimuthal vector potential: $A^\phi = \frac{B_0}{2} \frac{R_0^3}{R_0^3 + r^3} r \sin\theta$



Shock expansion and ejecta energy

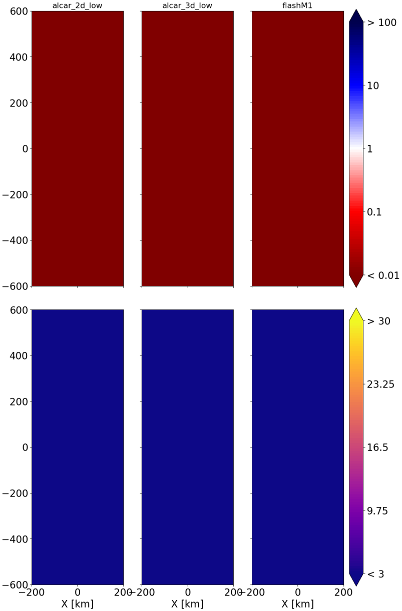


- Prompt explosion for all simulations, but with different efficiency.
- `AENUS-ALCAR` (`3DnSNe-IDSA`) produces the fastest (slowest) shock expansion and the most (least) powerful explosion.
- 2D vs 3D: opposite trends between the codes

Explosion dynamics

$p_{\mathrm{mag}}/p_{\mathrm{gas}}$

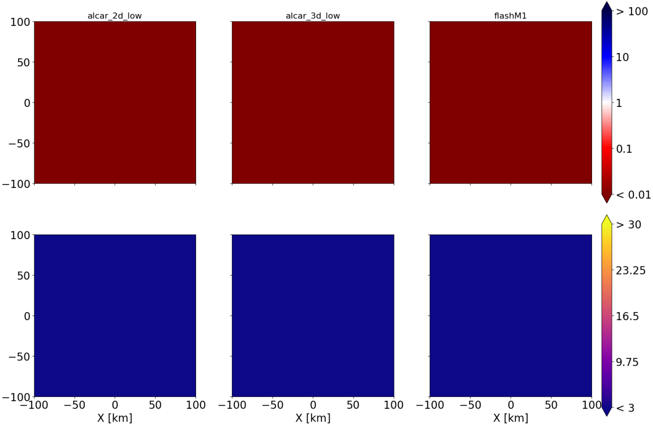
Specific entropy



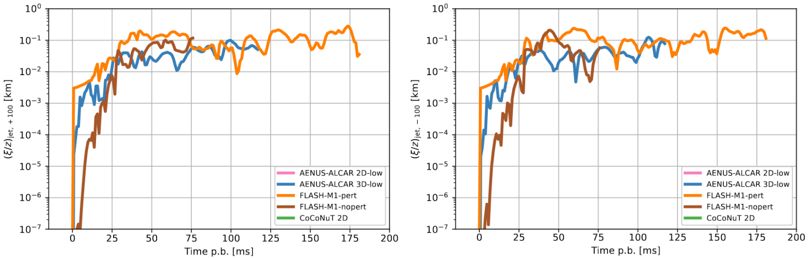
Explosion dynamics

$p_{\mathrm{mag}}/p_{\mathrm{gas}}$

Specific entropy



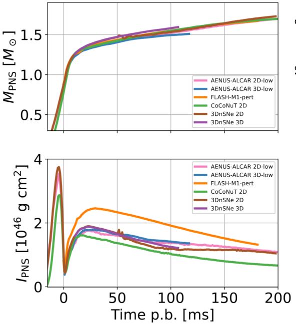
The kink instability



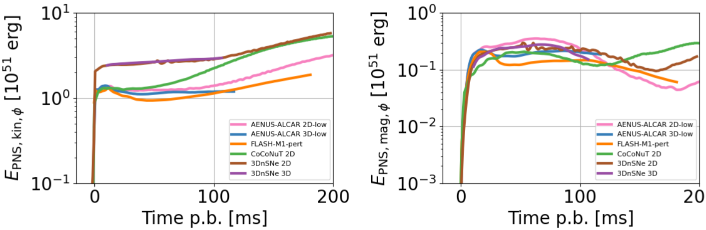
- Displacement of the jet's barycenter over time at $r = 100$ km
- Consistent saturation of the non-axisymmetric modes of the kink
- Coherence of the outflow with both Cartesian and spherical grids

(Mösta et al., 2014)

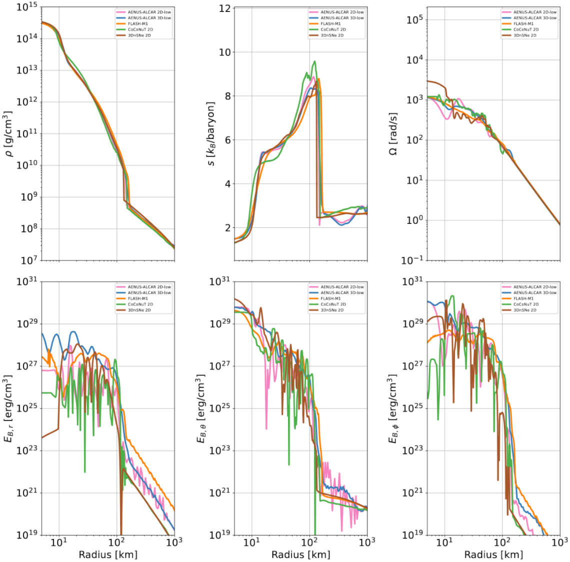
The proto-neutron star (I)



- PNS mass and moment of inertia consistent
- `FLASH-M1` model significantly more oblate (no lapse function)
- Significant deviations in rotational energy, initial excess for `3DnSNe-IDSA` models
- Toroidal magnetic energy consistent up to $t \sim 150$ ms p.b.



The proto-neutron star (II)



Radial profiles for density, entropy, and the magnetic field in good agreement

Conclusions

- ✓ Qualitative agreement among all different codes at the early stages of the explosion
- ✓ Quantitative deviations in the explosion efficiency and shock radius expansion within the first 100 ms
- ✓ Proto-neutron star mass consistently reproduced, but deviations in rotation rates and toroidal magnetic field
- ✓ No disruption of the outflow by the kink instability, but significant differences in the azimuthal structure

Future goals

- ○ Inclusion of more 2D and 3D models
- ○ Impact of resolution and convergence
- ○ Extension of models to later times
- ○ Analysis of multi-messenger signals

Conclusions

- ✓ Qualitative agreement among all different codes at the early stages of the explosion
- ✓ Quantitative deviations in the explosion efficiency and shock radius expansion within the first 100 ms
- ✓ Proto-neutron star mass consistently reproduced, but deviations in rotation rates and toroidal magnetic field
- ✓ No disruption of the outflow by the kink instability, but significant differences in the azimuthal structure

Future goals

- ○ Inclusion of more 2D and 3D models
- ○ Impact of resolution and convergence
- ○ Extension of models to later times
- ○ Analysis of multi-messenger signals

Merci de votre attention !

References I

Aguilera-Dena, D. R., Langer, N., Antoniadis, J., and Müller, B. (2020). Pre-collapse Properties of Superluminous Supernovae and Long Gamma-Ray Burst Progenitor Models. arXiv:2008.09132 [astro-ph]. arXiv: 2008.09132.

Burrows, A., Dessart, L., Livne, E., Ott, C. D., and Murphy, J. (2007). Simulations of Magnetically Driven Supernova and Hypernova Explosions in the Context of Rapid Rotation. The Astrophysical Journal, 664(1):416.

Dessart, L., Burrows, A., Livne, E., and Ott, C. D. (2008). The Proto-Neutron Star Phase of the Collapsar Model and the Route to Long-Soft Gamma-Ray Bursts and Hypernovae. \apjl, 673:L43.

Dessart, L., O'Connor, E., and Ott, C. D. (2012). THE ARDUOUS JOURNEY TO BLACK HOLE FORMATION IN POTENTIAL GAMMA-RAY BURST PROGENITORS. The Astrophysical Journal, 754(1):76.

References II

Gao, H., Zhang, B., and Lü, H.-J. (2016). Constraints on binary neutron star merger product from short GRB observations. Physical Review D, 93(4).

Gompertz, B. P., O'Brien, P. T., and Wynn, G. A. (2014). Magnetar powered GRBs: explaining the extended emission and X-ray plateau of short GRB light curves. Monthly Notices of the Royal Astronomical Society, 438:240–250.

Inserra, C., Smartt, S. J., Jerkstrand, A., Valenti, S., Fraser, M., Wright, D., Smith, K., Chen, T.-W., Kotak, R., Pastorello, A., Nicholl, M., Bresolin, F., Kudritzki, R. P., Benetti, S., Botticella, M. T., Burgett, W. S., Chambers, K. C., Ergon, M., Flewelling, H., Fynbo, J. P. U., Geier, S., Hodapp, K. W., Howell, D. A., Huber, M., Kaiser, N., Leloudas, G., Magill, L., Magnier, E. A., McCrum, M. G., Metcalfe, N., Price, P. A., Rest, A., Sollerman, J., Sweeney, W., Taddia, F., Taubenberger, S., Tonry, J. L., Wainscoat, R. J., Waters, C., and Young, D. (2013). Super-luminous Type Ic Supernovae: Catching a Magnetar by the Tail. The Astrophysical Journal, 770(2):128.

References III

Just, O., Obergaulinger, M., and Janka, H.-T. (2015). A new multidimensional, energy-dependent two-moment transport code for neutrino-hydrodynamics. \mnras, 453:3386–3413.

Kasen, D. and Bildsten, L. (2010). Supernova Light Curves Powered by Young Magnetars. The Astrophysical Journal, 717(1):245.

Kuroda, T. and Umeda, H. (2010). THREE-DIMENSIONAL MAGNETOHYDRODYNAMICAL SIMULATIONS OF GRAVITATIONAL COLLAPSE OF A 15 M STAR. The Astrophysical Journal Supplement Series, 191(2):439–466.

Lü, H.-J., Zhang, B., Lei, W.-H., Li, Y., and Lasky, P. D. (2015). The Millisecond Magnetar Central Engine in Short GRBs. The Astrophysical Journal, 805(2):89.

Masada, Y., Takiwaki, T., and Kotake, K. (2015). Magnetohydrodynamic Turbulence Powered by Magnetorotational Instability in Nascent Protoneutron Stars. The Astrophysical Journal, 798:L22.

References IV

Masada, Y., Takiwaki, T., and Kotake, K. (2022). Convection and Dynamo in Newly Born Neutron Stars. The Astrophysical Journal, 924:75.

Metzger, B. D., Quataert, E., and Thompson, T. A. (2008). Short-duration gamma-ray bursts with extended emission from protomagnetar spin-down. \mnras, 385:1455–1460.

Müller, B. and Janka, H.-T. (2015). Non-radial instabilities and progenitor asphericities in core-collapse supernovae. Monthly Notices of the Royal Astronomical Society, 448:2141–2174.

Mösta, P., Richers, S., Ott, C. D., Haas, R., Piro, A. L., Boydstun, K., Abdikamalov, E., Reisswig, C., and Schnetter, E. (2014). Magnetorotational Core-collapse Supernovae in Three Dimensions. The Astrophysical Journal, 785(2):L29. Citation Key Alias: mosta2014a.

References V

Nicholl, M., Smartt, S. J., Jerkstrand, A., Inserra, C., McCrum, M., Kotak, R., Fraser, M., Wright, D., Chen, T.-W., Smith, K., Young, D. R., Sim, S. A., Valenti, S., Howell, D. A., Bresolin, F., Kudritzki, R. P., Tonry, J. L., Huber, M. E., Rest, A., Pastorello, A., Tomasella, L., Cappellaro, E., Benetti, S., Mattila, S., Kankare, E., Kangas, T., Leloudas, G., Sollerman, J., Taddia, F., Berger, E., Chornock, R., Narayan, G., Stubbs, C. W., Foley, R. J., Lunnan, R., Soderberg, A., Sanders, N., Milisavljevic, D., Margutti, R., Kirshner, R. P., Elias-Rosa, N., Morales-Garoffolo, A., Taubenberger, S., Botticella, M. T., Gezari, S., Urata, Y., Rodney, S., Riess, A. G., Scolnic, D., Wood-Vasey, W. M., Burgett, W. S., Chambers, K., Flewelling, H. A., Magnier, E. A., Kaiser, N., Metcalfe, N., Morgan, J., Price, P. A., Sweeney, W., and Waters, C. (2013). Slowly fading super-luminous supernovae that are not pair-instability explosions. Nature, 502(7471):346.

Obergaulinger, M. and á. Aloy, M. (2017). Protomagnetar and black hole formation in high-mass stars. Monthly Notices of the Royal Astronomical Society: Letters, 469(1):L43–L47.

References VI

Obergaulinger, M. and Aloy, M. (2021). Magnetorotational core collapse of possible GRB progenitors - III. Three-dimensional models. Monthly Notices of the Royal Astronomical Society, 503:4942–4963. ADS Bibcode: 2021MNRAS.503.4942O tex.ids= obergaulinger2020, obergaulinger2020b arXiv: 2008.07205.

O'Connor, E. P. and Couch, S. M. (2018). Two-dimensional Core-collapse Supernova Explosions Aided by General Relativity with Multidimensional Neutrino Transport. The Astrophysical Journal, 854:63.

Schneider, F. R. N., Ohlmann, S. T., Podsiadlowski, P., Röpke, F. K., Balbus, S. A., Pakmor, R., and Springel, V. (2019). Stellar mergers as the origin of magnetic massive stars. Nature, 574(7777):211. Citation Key Alias: schneider2019a.

Shibata, M., Liu, Y. T., Shapiro, S. L., and Stephens, B. C. (2006). Magnetorotational collapse of massive stellar cores to neutron stars: Simulations in full general relativity. Physical Review D, 74(10).

References VII

Steiner, A. W., Hempel, M., and Fischer, T. (2013). Core-collapse Supernova Equations of State Based on Neutron Star Observations. The Astrophysical Journal, 774:17.

Takiwaki, T., Kotake, K., and Sato, K. (2009). Special Relativistic Simulations of Magnetically Dominated Jets in Collapsing Massive Stars. The Astrophysical Journal, 691(2):1360.

Takiwaki, T., Kotake, K., and Suwa, Y. (2016). Three-dimensional simulations of rapidly rotating core-collapse supernovae: finding a neutrino-powered explosion aided by non-axisymmetric flows. Monthly Notices of the Royal Astronomical Society: Letters, 461(1):L112–L116.

Winteler, C., Käppeli, R., Perego, A., Arcones, A., Vasset, N., Nishimura, N., Liebendörfer, M., and Thielemann, F.-K. (2012). MAGNETOROTATIONALLY DRIVEN SUPERNOVAE AS THE ORIGIN OF EARLY GALAXY r -PROCESS ELEMENTS? The Astrophysical Journal, 750(1):L22.

References VIII

Woosley, S. and Heger, A. (2007). Nucleosynthesis and remnants in massive stars of solar metallicity. Physics Reports, 442(1-6):269–283.

Woosley, S. E. and Heger, A. (2006). The Progenitor Stars of Gamma-Ray Bursts. The Astrophysical Journal, 637(2):914.

Zhang, B. and Mészáros, P. (2001). Gamma-Ray Burst Afterglow with Continuous Energy Injection: Signature of a Highly Magnetized Millisecond Pulsar. The Astrophysical Journal, 552(1):L35–L38.