Usage Report for Fiscal Year 2024

Project Title:

Hydrodynamical modelling of binary interaction-powered supernovae

Name:
○Ryosuke Hirai (1)

Laboratory at RIKEN:
(1) Cluster for Pioneering Research, Astrophysical Big Bang Laboratory

1. Background and purpose of the project, relationship of the project with other projects

Supernova explosions are the final fates of massive stars, giving birth to neutron stars and black holes. It is known that the majority of massive stars are born in binary or higher order multiple systems, and thus it is expected that many supernova explosions should occur in the presence of a close-by companion star. In a previous study (Hirai & Podsiadlowski 2022), I investigated the consequence of direct collisions of new-born neutron stars and their companion stars straight after supernova. We predicted that in some situations this could lead to accretion onto the neutron star that can power the supernova from inside, causing multiple bumps in the light curve. Last year, a supernova SN2022jli was detected with these characteristics, strongly supporting this scenario.

In this project, I aim to extend my previous study in an attempt to model the details of SN2022jli. Specifically, I consider the expansion of the companion due to heating by the supernova ejecta (Hirai et al. 2018, Ogata, Hirai, Hijikawa 2021, Hirai 2023). With this expansion, the probability of direct interaction is much higher than without expansion, and the density of the interacting layers are much lower. This could lead to much more stable interactions for extended periods of time, in line with the sustained periodicity in SN2022jli.

Furthermore, the accretion of envelope material onto the new-born neutron star could drive strong feedback, which in turn influences the dynamics of the accretion. The energy released in the feedback could interact with the dilute envelope, powering the supernova light curve in non-trivial ways. One of the main goals of this project is to make predictions of how the accretion feedback could impact the light curve and whether this matches that of SN2022jli.

2. Specific usage status of the system and calculation method

To model the interaction between supernova-heated stars and new-born neutron stars, I use my own hydrodynamics code HORMONE (Hirai et al. 2016), which has recently been OpenMP + MPI-parallelized and scales extremely well with problem size. It solves the Euler equations based on a Godunov-type scheme, coupled with my original hyperbolic self-gravity solver. The basic setup of the simulation follows that of Hirai & Podsiadlowski 2022. As our fiducial model, we choose a 5 Msun companion star paired with a 1.5 Msun neutron star on an orbit with eccentricity e=0.5. The orbital period is fixed to 12.5d to match the periodicity of SN2022jli.

There are substantial updates made to the code to account for additional effects. First, in order to resolve the companion at sufficiently high levels, I enabled the code to deal with non-inertial frames, where the coordinate origin is fixed to the centre of mass of the companion. Secondly, I inject heat to the companion star envelope following the method of Hirai et al. 2018; Ogata et al. 2021 to represent the heat injected through supernova ejecta-companion interaction. Finally, I implement the effect of accretion feedback from the point particle representing the neutron star. I compare results obtained with different forms of feedback, (i) no feedback, (ii) pressure feedback, and (iii) bipolar outflow. Typically, each simulation used 256 compute threads.

I also compute the expected supernova light curve based on the hydrodynamic simulations. For this, I adapt the module that I developed for Grishin et al. 2021, extending it for multi-frequencies so that we can obtain effective temperature and photospheric radius estimates.

3. Result

Based on our simulations, we find that the supernova-heating of the companion is extremely important to induce large amounts of mass accretion onto the new-born neutron star.

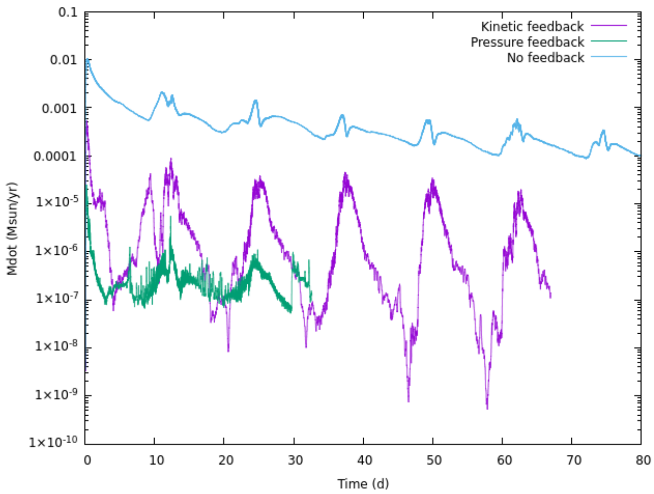

Fig 1. Comparison of mass accretion rates between the three different kinds of feedback implementation

In Fig. 1, I plot the time evolution of the mass accretion rate onto the neutron star. Due to the moderately high eccentricity (e=0.5), there are strong periodic modulations as the neutron star passes through layers of different depths inside the envelope. In the absence of feedback (sky blue curve), the accretion rate reaches up to 10^{-2} Msun/yr, slightly exceeding the required accretion rate to reproduce the luminosity of SN2022jli. The amplitude of the modulations is about one order of magnitude, which is a factor ~3-5 higher than the undulation amplitude in SN2022jli.

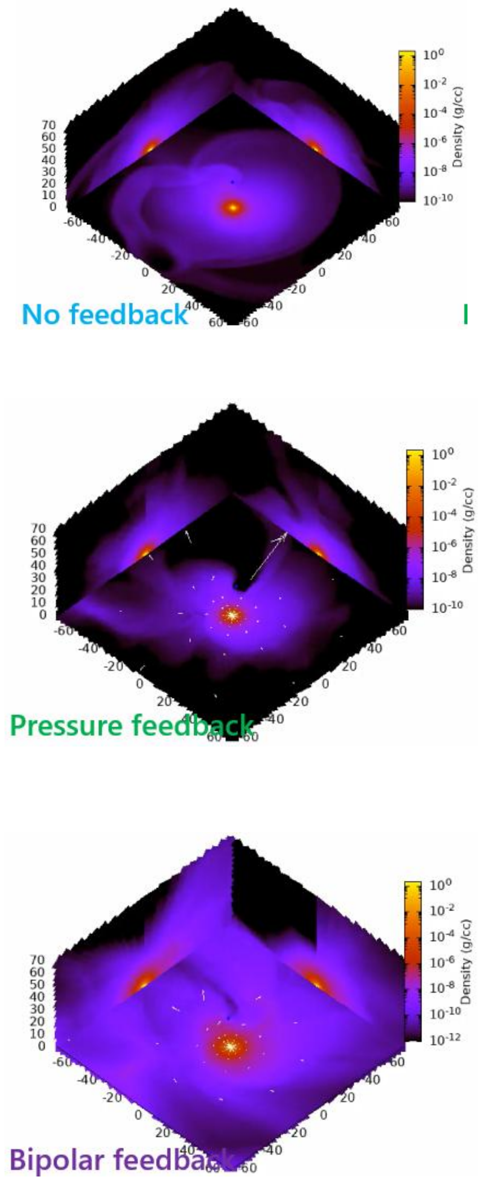

Fig 2. Snapshots of the 3D hydrodynamic simulations of post-supernova binary interactions

Fig. 2 compares snapshots of the simulations run with different forms of feedback. The visual differences are striking, indicating that the form of feedback is crucial for determining the overall dynamics. With spherically symmetric feedback, the accreting material is pushed away, creating a cavity around the neutron star. As a result, the accretion rate is regulated to a value determined by the input parameters of the feedback (Fig 1, green curve). Whereas with bipolar feedback, the accretion rate is sustained at high levels (Fig 1, purple curve) as the accretion occurs along the equatorial plane while the feedback is directed polewards. Although there is some quenching of the accretion rate due to the feedback, it still maintains the required magnitude to explain the luminosity of SN2022jli.

Finally, we construct mock light curves based on our model with bipolar feedback. Given the high level of asymmetry in the system, we compute the light curve from various viewing angles to explore the viewing angle-dependence. Note that we do not add the contribution from the supernova explosion itself, which should be the dominant light source at early times.

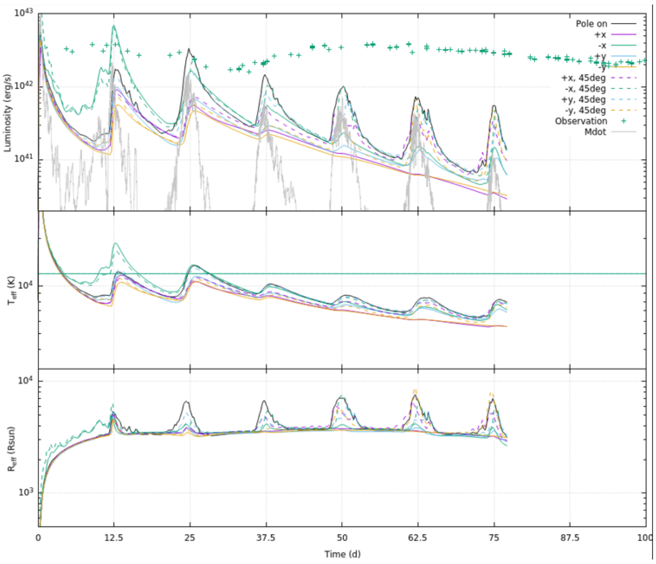

Fig 3. Light curve simulated from the bipolar feedback model

We show our results in Fig. 3, with the observed light curve of SN2022jli overplotted with green crosses. We manage to reproduce several key characteristics of SN2022jli; the periodic bumps and overall decline. The amplitude of the bumps is strongly viewing angle-dependent, with larger amplitudes when viewed from the pole and smaller amplitudes from the equator. It is also worth noting that the bump amplitude is not the same as the accretion rate amplitude, as the former is smeared out by the reprocessing of light by the dense surrounding envelope. The low undulation amplitude of SN2022jli implies a rather edge-on viewing angle based on our simulations.

4. Conclusion

We model the light curve of SN2022jli through 3D hydrodynamic simulations, based on the hypothesis that the periodic undulations were powered by accretion feedback from a neutron star on an eccentric orbit around the companion star. Our preliminary model already reproduces key qualitative features of the observed light curve. We predict a diverse range of possible light curve morphologies depending on the viewing angle, implying that more periodically undulating supernovae with larger amplitudes may be observed in the future.

5. Schedule and prospect for the future

While our models reproduce several key aspects of the SN2022jli light curve, there are still major discrepancies from SN2022jli, including the magnitude of the luminosity and the decline rate. However, we stress that the model we simulate is just one representative model and many more parameter dependencies should be investigated. For example, different choices for the companion mass and orbital eccentricity could lead to different penetration depths, which could strongly impact the accretion rate. Such parameter dependencies will be explored in future work.

Usage Report for Fiscal Year 2024

Fiscal Year 2024 List of Publications Resulting from the Use of the supercomputer

[Conference Proceedings]

[1] Ryosuke Hirai, “Post-supernova binary interactions”, Bulletin de la Société Royale des Sciences de Liège [En ligne], Volume 93 - Année 2024, No 3 - 41st Liège International Astrophysical Colloquium, 206-215 (2024)

[Oral presentation]

[1] Ryosuke Hirai, “Post-supernova binary interactions: the tale of SN2022jli”, 41st Liège International Astrophysical Colloquium: The eventful life of massive star multiples, 17th July 2024, University of Liege, Belgium

[2] Ryosuke Hirai, “Post-supernova binary interactions: the tale of SN2022jli”, The Progenitors of Supernovae and their Explosions, 19th August 2024, Dali, China

[3] Ryosuke Hirai, "Supernovae in the context of binary evolution", Stars in Brisbane & 10th Australian Exoplanet Workshop, 4th November 2024, University of Southern Queensland, Australia

[4] Ryosuke Hirai, “Supernovae in binary systems”, Theories of Astrophysical Big Bangs 2025, 19th February 2025, RIKEN, Japan