

Posudek práce

předložené na Matematicko-fyzikální fakultě
Univerzity Karlovy

- posudek vedoucího posudek oponenta
 bakalářské práce diplomové práce

Autor: Bc. David Kománek
Název práce: Rekrece hmoty hvězdných větrů a supernov na černou díru
Studijní program a obor: Astronomie a astrofyzika
Rok odevzdání: 2025

Jméno a tituly oponenta: RNDr. Ondřej Chrenko, Ph.D.
Pracoviště: Astronomický ústav MFF UK
Kontaktní e-mail: chrenko@sirrah.troja.mff.cuni.cz

Odborná úroveň práce:

- vynikající velmi dobrá průměrná podprůměrná nevyhovující

Věcné chyby:

- téměř žádné vzhledem k rozsahu přiměřený počet méně podstatné četné závažné

Výsledky:

- originální původní i převzaté netriviální kompilace citované z literatury opsané

Rozsah práce:

- veliký standardní dostatečný nedostatečný

Grafická, jazyková a formální úroveň:

- vynikající velmi dobrá průměrná podprůměrná nevyhovující

Tiskové chyby:

- téměř žádné vzhledem k rozsahu a tématu přiměřený počet četné

Celková úroveň práce:

- vynikající velmi dobrá průměrná podprůměrná nevyhovující

Slovní vyjádření, komentáře a připomínky oponenta:

The thesis presented by D. Kománek deals with interactions between the interstellar medium (ISM) and an embedded single massive star that eventually evolves into a black hole. During its lifetime, the progenitor star injects strong winds and ionizing radiation into its surroundings, creating a structured bubble in the ISM. The main objective of this thesis is to assess whether a fraction of the interstellar bubble material can be re-accreted once the star evolves into a black hole, thereby increasing its mass. Investigating such a process is timely because black hole masses are often used to constrain their origins. Therefore, understanding the contribution of interstellar bubbles to the black-hole mass budget is of high relevance.

The problem at hand is physically complex. This is because the evolution of the progenitor star through the main sequence and the late stages (e.g. the Wolf-Rayet phase, if applicable) sculpts the ISM with winds that vary in time. All these stages must be accounted for in order to obtain realistic conditions for studying re-accretion of bubble material. Two scenarios for re-accretion are addressed in the thesis. Scenario 1 assumes that the massive star collapses directly into a black hole. Scenario 2 assumes that black hole formation proceeds through a core-collapse supernova explosion.

Various methods of numerical modeling are applied in the thesis. First, 1D stationary profiles of the interstellar bubble near the contact discontinuity are computed, resolving at fine detail the transition between the outer bubble regions and the region where the stellar wind is affected by the reversed shock. It is noteworthy that these stationary solutions are computed by the HECTOR code, developed by D. Kománek as part of the thesis. The stationary solutions are then used to validate 1D hydrodynamic simulations obtained with the publicly available FLASH code. These 1D FLASH simulations constitute the bulk of the numerical results and are used for a broad parametric study of the long-term evolution of the interstellar bubble and re-accretion onto the central object. The parameter space involves the particle density of the progenitor cloud, its gravitational binding energy, the mass of the central star, and metallicity. Two specific 1D cases that appear favorable for re-accretion are then used as initial conditions for full-fledged 3D simulations with the FLASH code. Regarding the implemented physics, the simulations include thermal conduction, tabulated radiative cooling, ionizing radiation (in 1D), gravity and self-gravity, wind and supernova material injection, and gas accretion onto the central body using the cell sink approach (dictated by resolution limitations).

The final results of the thesis are somewhat negative in terms of re-accretion—the process seems highly unlikely because the inner bubble regions become too rarified (either due to late stellar winds or the influence of the supernova). However, this conclusion does not make the results any less valuable. The compilation of various profiles of wind-driven ISM bubbles presented in the thesis provides results that could be useful on their own.

In summary, the applicant clearly demonstrates critical scientific thinking and the ability to conduct highly original research using various complementary methods. Therefore, I recommend the thesis for acceptance and suggest it be rated as excellent.

A list of **minor comments** follows; major comments that should be answered during the thesis defense are appended in a standalone final section of this report:

- Section 2.3.1 mentions that "winds are implemented by continuously inserting mass and thermal energy into the simulation". But what about momentum—is it inserted as well? From Eq. (2.2) this indeed appears to be the case.
- In Figure 2.1, the meaning of the dashed curves is not explained. I assume they correspond to the terminal velocity axis.
- Following Eq. (2.14), the ejection radius R_{ej} is defined to span at least 5 grid cells. It would be useful to provide some characteristic values of cell sizes and R_{ej} .

- Following Eq. (2.23), it is discussed that the Courant condition related to thermal conduction (in its explicit form) would be the most restrictive for the time step size. This is not evident from the equations alone and should be supported either by references, or by an order-of-magnitude comparison with other applicable CFL constraints.
- End of Section 2.3.4: it is mentioned that the backward Euler and Crank-Nicholson schemes lead to similar results. But the very next sentence claims that the Crank-Nicholson scheme tends to be unstable. So there seems to be some mismatch between the two sentences which I do not fully understand.
- End of Section 2.3.7: to my understanding, this is the first time the thesis mentions that 1D simulations are remapped to 3D. This close relation between 1D and 3D setups should be outlined earlier in the manuscript.
- Section 2.5 dealing with HECTOR: it would be useful to include the most important parts of the source code in an Appendix and document the underlying algorithm. I noticed that the source code has been uploaded in the Student Information System along with the thesis, but these online sources are not referenced in the manuscript (I could have easily missed them).
- Page 42 and elsewhere: when discussing reflected waves traveling toward the black hole, it would be useful to show the negative portion of the velocity axis (at least partially) to offset the $v = 0$ line from the radial axis.
- Section 3.3: it is mentioned that the 1D resolution cannot be achieved in 3D. But there is no discussion of the computational resources needed for 3D simulations, nor of the parallel scaling of the code. So I am skeptical of this claim and believe that by running on more powerful clusters (or simply running longer), a resolution improvement could be achieved in 3D.
- The use of adaptive mesh refinement (AMR) is mentioned very late in the thesis—only in Figure captions 3.12 and 3.14. This functionality of FLASH would certainly deserve a broader discussion. How many levels of refinement are permitted? Are the results heavily dependent on AMR?
- Typos/style improvements. Page 18: Reflected wave are created → waves are created. Page 19, 23, and elsewhere: Some citations seem to be poorly formatted, for instance Tenorio-Tagle, Bodenheimer, et al. (1990) or Truelove and Christopher F. McKee (1999). Page 26: "Flash" should be typeset using `\textsc` for consistency. Page 34 and Table 3.1: when specifying a range of values, it is customary to state the physical unit only once (e.g. $10^2\text{--}10^3\text{ cm}^{-3}$). Figure 3.4 and similar: it would be helpful to mark individual regions of the bubble (the free wind, shocked wind, HII, etc). Page 37: "the shell is outside the scope of our simulations, since..." → "the evolution of the shell is outside the scope of our simulations, but we point out that...".

Případné otázky při obhajobě a náměty do diskuze:

I have one *major comment*:

- In my opinion, the discussion of the 3D simulations (Section 3.3) is very brief and would benefit from being expanded. In particular, the fact that the most favorable 1D simulation with re-accretion does not lead to re-accretion in 3D is not explained sufficiently. What is the physical mechanism that prevents re-accretion in 3D? Some problematic parts of the last paragraph of Section 3.3.1 are:

- The sentence "the second panel shows the bubble interior cooling faster in 1D" seems to contradict the sentence "the cooling in the 3D simulations is overestimated".
- The sentence "The density in the center is much higher in the 1D simulation", which refers to the third panel of Fig. 3.13, cannot be clearly confirmed unless the inner region ($r \lesssim 1$ pc) is displayed in detail (the curves are too blended together in Fig. 3.13).

Additional questions dealing with *technical aspects* of the model:

- Section 2.3.6: I have two questions regarding the treatment of accretion onto the central body. First, you mention that the gas density is removed from the central grid cell to mimic accretion. Does this density removal lead to any changes in the local temperature via the equation of state? If so, are such changes realistic? Second, you mention the use of passive scalars to trace the origin of accreted gas. But passive scalars are not discussed anywhere in the Results section. Why?
- When discussing radiative cooling in Section 2.3.3 (Page 24), you write "we assume that the gas is optically thin so all of the energy is radiated away". Do you really mean **all** of the energy? Please elaborate.
- The gravitational potential of the central compact object contains a Plummer-type smoothing length (Eq. 2.25). Does the efficiency of re-accretion depend on the choice of the smoothing length or is this parameter of no importance? What is its value compared to the grid cell size?
- Section 2.4: For your 3D model setup, Cartesian coordinates are used. Is there a reason spherical coordinates were not chosen instead? One might naively expect that spherical coordinates are better suited to capture the initial spherically symmetric geometry of the problem.

Práci:

- doporučuji
- nedoporučuji

uznat jako diplomovou.

Navrhuji hodnocení stupněm:

- výborně
- velmi dobře
- dobře
- neprospěl

Místo, datum a podpis oponenta:

Praha, 3. června 2025