Mem. S.A.It. Vol. 88, 274

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Calculating the average opacity for core-collapse supernovae

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Abstract. We present a systematic analysis for estimating the average opacity in different types of core-collapse supernovae that can be used as the constant Thompson-scattering opacity of the ejecta in simplified semi-analytic models. To use these average opacities self-consistently during light curve (LC) fit we have to estimate their values from hydrodynamic simulations. In this analysis we first generate MESA stellar models with different physical parameters (initial mass, metallicity, rotation). Then we synthesize SN LCs from these models with SNEC code and calculate the Rosseland mean opacity in every mass element. Finally, we compute the average opacities by integrating these Rosseland mean opacities. As a result we find that the average opacities from our calculations show adequate agreement with the opacities generally used in previous studies.

1. Introduction

Core-collapse supernovae (CCSNe) form a diverse group of explosion events, but all of them are believed to originate from the death of massive stars ($M > 8M_{\odot}$). The classification of these events is based on both their spectral features and LC properties. CCSNe can be divided into several groups: Type Ib/Ic, Type IIP, Type IIb, Type IIL, and Type IIn (Filippenko 1997).

One possibility to estimate the initial properties of these events is to fit their LC with semi-analytic models that contain many assumptions. One of the strongest simplification in most of these LC models is the so-called constant opacity approximation, which means that the opacity of the ejecta is constant in both space and time and also equal to the Thompson-scattering opacity (κ_{Th}). The advantage of this approximation is that κ_{Th} depends only on the average chemical composition of the supernova ejecta. But it should be kept in mind that the final chemical composition of the progenitor can be influenced by several physical processes, which determine the mass loss history of the exploding star. In spite of this fact, in the literature the generally used approach is that the average opacity is only a model parameter that has no strong connection with the chemical composition. Thus, for example, its value should be about 0.3 - 0.4 cm^2/g for a H-dominated Type IIP SN, and approximately 0.1 - 0.3 cm^2/g for Type Ib/Ic events.

In this paper we aim to calculate the average opacities that are self-consistent with the chemical composition of typical CCSNe.

This paper is organized as follows. In Sect. 2 and 3. we briefly describe the applied method, and the estimated average opacities, respectively. Finally, Sect. 4 summarizes the main conclusions of this paper.

2. Calculating the average opacity

During this work we approximate the average opacities via synthesized light curve models. The internal structure of the progenitor stars are derived from stellar evolution models created by the MESA code (Paxton et al. 2013) with different initial physical parameters from pre-main sequence up to core-collapse. It should be kept in mind, that the opacity calculation in this phase is based on the combination of opacity tables from OPAL, Ferguson et al. (2005), and Cassisi et al. (2007).

The subsequent hydrodynamic evolutions are followed by the 1D Lagrangian supernova explosion code, SNEC (Morozova et al. 2015). In all calculated models the 'thermal bomb' explosion scheme are used, in which the total energy of the explosion is injected into the model with an exponential decline both in time and in mass coordinate. The SNEC code calculates the opacity in each grid point of the model from Rosseland mean opacity tables for different chemical compositions, temperatures, and densities. For this process an opacity minimum is also needed for the code. In our simulations the opacity boundary was 0.24 cm^2/g for the pure metal layer and 0.01 cm^2/g for the solar composition envelope (Bersten et al. 2011). Thus, in SNEC the opacity at each time and grid point is chosen as the maximum value between the calculated Rosseland mean opacity and the opacity boundary for the corresponding composition.

In each case the original SNEC opacity output files are used. In every time-step we integrate the opacity (Nagy & Vinko 2016) from the mass coordinate of the neutron star ($M_0 = 1.34 M_\odot$) up to the mass coordinate of the photosphere (M_{ph}):

$$\kappa(M_{ph}) = \frac{1}{M_{ph} - M_0} \int\limits_{M_0}^{M_{ph}} \kappa \, dm \, . \tag{1}$$

This way we get rid of the time-dependence of the calculated opacities.

Since the opacity in semi-analytic models are constant in space and time, the time-averaged opacity ($\overline{\kappa}$) is defined by integrating the $\kappa(M_{ph})$ values from several days after the shock breakout (t_0) up to t_{end} as

$$\overline{\kappa} = \frac{1}{t_{end} - t_0} \int\limits_{t_0}^{t_{end}} \kappa(M_{ph}) \, dt \, . \tag{2}$$

During our study for Type IIP and Type IIb supernova models we use the two-component configuration, which contains a dense core and an extended, low-mass outer shell (e.g. Nagy & Vinko 2016). Thus, we separately calculate the average opacity for both the early cooling phase and the late-time photospheric phase. In the early phase, t_0 is chosen to be 5 days after the moment of the shock breakout, while t_{end} is defined as the termination of the cooling phase when the opacity drops rapidly. For the second LC phase, t_0 is equal to t_{end} of the early phase, and the integration continues up to the end of the photospheric phase. Moreover to receive comparable result with other semi-analytic models (e.g., Arnett & Fu 1989), we also determine the average opacity by integrating $\kappa(M_{ph})$ from 5 days up to the end of the photospheric phase.

3. Results

To estimate the average opacity for different core-collapse supernovae we systematically change various physical parameters that determine the mass-loss history of the model star.

One of the most important parameters that induces changes in the chemical composition and also affects mass-loss, is the initial mass of the progenitor. During our calculations the 'Dutch' wind-scheme is used to model the mass-loss in the AGB and RGB phase. In MESA this scenario combines the results form Glebbeek et al. (2009), Vink et al. (2001) and Nugis & Lamers (2000) to approximate an acceptable mass-loss history for a massive star. Fig. 1 a) shows that models with moderate mass-loss receive lower opacities. As we expect, these smaller mass-loss rates represent models with lower mass, which means that if we want to be self-consistent while modeling the supernova LCs, we have to use slightly

Table 1. Average opacities for different types of CCSNe

Parameter	IIP	IIb	Ib	Ic
M_{ej} ($M_\odot$)	16.5	7.5	4.5	3.5
t_{shell} (day)	13 ± 1	9 ± 1	-	-
$\overline{\kappa}_{shell}$ (cm^2/g)	0.381 ± 0.01	0.293 ± 0.02	-	-
$\overline{\kappa}_{core}$ (cm^2/g)	0.20 ± 0.01	0.193 ± 0.01	0.182 ± 0.01	0.10 ± 0.01
$\overline{\kappa}_{total}$ (cm^2/g)	0.213 ± 0.03	0.195 ± 0.02	0.182 ± 0.01	0.10 ± 0.01

lower opacities (0.18 - 0.2 cm^2/g) than usual for Type IIP SNe with 8 - 10 $M_\odot$ ejecta.

The intensity of the stellar wind could also be an important parameter. In MESA we are able to change the strength of the wind-scheme with a scaling factor. Nevertheless, the results of this analyses show that the stellar wind intensity influence neither the generated LCs nor the calculated average opacities significantly. So, the intensity of the mass-loss processes cannot be determined by fitting the LC of the SNe.

Another significant physical parameter which indicates mass-loss during the stellar evolution, is the metallicity of the exploding star. The results show that, as we expect, stars with lower metallicity are able to keep most of their hydrogen and helium layers. Thus, the opacity values for low-metallicity stars become higher than opacities of a solar-like object (Fig. 1 b)). So, if during LC fitting we get average opacities above ~ 0.35 cm^2/g, then it is plausible that the metal content of the progenitor was somewhat lower than the solar abundance of the heavier elements.

The surface rotation of the star may influence mass-loss as well. But as it can be seen in Fig. 1 c) the average opacities are not influenced significantly by the intensity of the surface velocity. Thus, from LC modeling the rotation of the progenitor cannot be determined.

Although the previously showed models could be relevant to approximate some physical processes that effect the mass-loss history, these results mainly refers to Type IIP-like progenitors. Thus, to compare the average opacity values for diverse types of CCSNe, we create different stellar structure models. In order to estimate the progenitor of a Type IIb, Ib and Ic SN, we remove the outer envelope of a MESA model manually. For the Type IIb model most of the outer H-rich envelope is cut off, so only ~ 1 $M_\odot$ of hydrogen remains. For the Type Ib model we remove the total H layer of the star, while for the Type Ic model we eliminate both the H and He envelope.

It can be seen in Table 1 that in the cooling phase $\overline{\kappa}$ is 0.4 cm^2/g for a Type IIP SN with a massive H-rich ejecta. However, the average opacity decreases to 0.3 cm^2/g for a Type IIb, which corresponds to a star that lost most of its H-rich envelope. In contrast, during the later phase, the average opacity of Type IIP and IIb is considerably similar, having a value of 0.2 cm^2/g. Although the two-component configuration is not an adequate solution for Type Ib and Ic events, the gained $\overline{\kappa}_{total}$ values are comparable to the average opacities from Type IIP and IIb model calculations. For Type Ib and Ic the average opacities are slightly lower, which agrees well with the expectations for the mass-loss history of these objects.

4. Conclusions

Although the constant Thompson-scattering opacity is not an adequate approximation for core-collapse supernova explosions because of the rapidly changing opacities in their ejecta, the calculated average opacities show reasonably good agreement with the frequently used constant opacities in the literature (Nakar & Sari 2010; Huang et al. 2015). Moreover, our results indicate that the two-component configuration could be relevant for modeling Type IIb and IIP SNe, because the gained average opacities for both the shell and the core component are similar to the expected values from the average chemical composition.

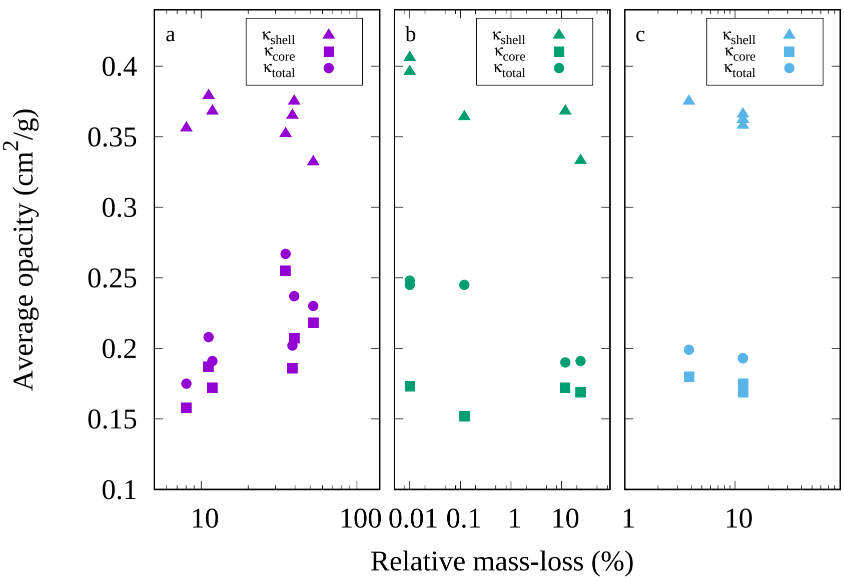

Fig. 1. The dependence of the average opacity on the relative mass-loss. Effect of changing the initial mass (panel a), the metallicity (panel b) and the strength of the surface rotation (panel c) of the progenitor model. In each case the various symbols represent the average opacities from different model approximations: one-component model (circle), shell (triangle) and core (square) configuration.

On the other hand, if we choose the opacity wisely during model fitting, we may estimate roughly the chemical composition of the progenitor. But it should be kept in mind that, because of the correlation of the model parameters we are not able to receive the exact configuration of the exploding star from the applied opacity values.

Acknowledgements. This research is supported by the GINOP-2.3.2-15-2016-00033 project which is funded by the Hungarian National Research, Development and Innovation Fund together with the European Union.

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