

**THE INITIAL MASS - REMNANT MASS RELATION AS A
FUNCTION OF THE INITIAL MASS, METALLICITY AND
ROTATION VELOCITY**

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Abstract

We briefly discuss the competing phenomena that control which fraction of a massive star collapses in the remnant and which fraction is ejected in the interstellar medium. In particular we firstly remind the key evolutionary properties that determine the final Mass-Radius relation and then we discuss our current calibration of the explosion. Eventually we present our current predictions for the masses of the remnants as a function of the initial mass, metallicity and initial rotation velocity.

1 Introduction

Massive stars end their life with an explosion whose energy is provided, broadly speaking, by the gravitational energy released by the collapse of the innermost part of the star down to nuclear densities. A reliable determination of the

relation between the initial mass of a star and the mass of the remnant is of vital importance because it allows to establish the connection between a given population of massive stars and the variegate zoo of systems that involve compact remnants, like, e.g., pulsars, low and high mass X-ray binaries, magnetars ecc. Moreover, many nuclear species are synthesized in the very deep interior of a massive star so that an uncertainty in the mass of the remnant mass directly reflects on the prediction of the yields produced in the deepest part of a massive star. Unfortunately we cannot currently predict the masses of the remnants because we cannot reliably, and routinely, follow the explosion of a star from first principles. Therefore we are forced to rely on calibrations that obviously require at fit to some observational data. The most used ones are the kinetic energy of the ejecta or the amount of ^{56}Ni ejected. In the following we will briefly describe our current predictions for the initial mass-remnant mass relation and we will show that masses of black holes as larger as $35M_{\odot}$ (as detected by the gravitational observatories LIGO-Virgo for GW 150914) ¹⁾ may be easily obtained in metal poor environments provided that the stars do not rotate significantly.

2 Discussion

The determination of the mass location that separates the remnant from the ejecta depends on the competition between the binding energy of the star and the outward moving shock wave generated by the collapse of the inner core. The run of the binding energy with the mass coordinate is the result of the hydrostatic evolution of the star that sculpts the final mass-radius (M-R) relation up to the onset of the collapse while the amount of energy gained by the shock wave depends on the fraction of neutrinos that return their energy to the star after having exited the neutrinosphere.

The final M-R relation (i.e. the binding energy) depends only on the hydrostatic evolution of the star and the main phenomena that contribute to sculpt this relation are the *instabilities*, thermal and/or rotation driven, plus mass loss. The first responsible for the final compactness of a star is the convective core in H burning because it basically determines the size of the key parameter that will drive all the following evolution, i.e. the He core mass. There are several phenomena that may affect the mass size of the convective core, the main ones being the efficiencies of a) the overshooting, b) the rotation

induced mixing and c) mass loss. A more effective overshooting and/or rotation induced mixing increase the He core mass while a more efficient mass loss reduces the size of the convective core (because it scales directly with the current mass of the star) and therefore the He core mass.

The second important instability that controls the final M-R relation is the extension and temporal evolution of the convective core in He burning. Also in this case the presence of some overshooting and/or induced mixing has the same effects already mentioned for the H burning, but now there is an additional product of the He burning that significantly affects the final M-R relation: the amount of ^{12}C left by the He burning in the Carbon Oxygen core. This is very important because it determines the efficiency of the C burning and its ability in advancing in mass. In fact, the lower the ^{12}C concentration at the central He exhaustion, the faster the advancing - in mass - of the C burning shell (because the shell has less fuel to burn in its way out but also because the formation of convective shell(s) is disfavored). Since an efficient active burning shell prevents the contraction of the overlying layers because its energy may sustain the outer layers, the more external the C burning shell is at the onset of the collapse, the more massive and compact the O-Ne core will be. Unfortunately there are a number of uncertainties that do not allow a reliable prediction of the amount of ^{12}C left by the He burning. In fact, it is well known that its final concentration depends not only on the competition among 3α , $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ and mixing but also on the possible occurrence of the so called "Breathing Pulses" (BP), convective instabilities that occur towards the end of the He burning and that may largely affect the final concentration of ^{12}C (we refer the reader to the paper by Castellani et.al (1985) ²⁾ for a deep discussion about the growth of these instabilities). While on average the BP reduce in number and efficiency as the initial mass increases, they may occur or not quasi erratically for even minor variations of the initial mass in the range of the massive stars. Such an occurrence could be responsible for the "chaotic" dependence of the final compactness of the stars as a function of the initial mass found recently ^{3) 4)}. We just started to address in detail such a problem and we will publish our findings shortly. Additional mixing phenomena occur during the more advanced burning phases (Ne, O and Si burnings) but in these cases the evolution is so fast that the rotation driven instabilities do not have time to develop efficiently and the mixing is just controlled by the thermal

instabilities, i.e. by the "standard" convection.

Though the detailed degree of compactness of a star is fully described by the M-R relation, it has been proposed ⁵⁾ the adoption of a single parameter, ξ , to describe in a concise way the degree of compactness of a star. ξ is the ratio between the Mass and the Radius computed at the mass coordinate of $2.5M_{\odot}$ at the onset of the core collapse:

$$\xi = M(M_{\odot})/R(10^3\text{km})_{(M=2.5)}$$

The choice of this parameter is based on the comparison between a set of 1D explosions computed for a variety of masses and their ξ parameter. The authors ⁵⁾ found that ξ , computed at a mass coordinate $M=2.5M_{\odot}$, discriminates well between models that fully collapse in a remnant and those that produce a successful explosion. In particular they found that a successful explosion is obtained for ξ values smaller than 0.45. More recently it has been questioned ^{3) 4)} the possibility of determine the final fate of a star on the basis of this simple parameter and the use of a double parameter has been proposed to determine the final fate of a massive star. For sake of simplicity in our paper ⁶⁾ we decided to adopt the simplest scenario ⁵⁾ to discriminate between stars that fully collapse and stars that explode successfully. Our grid of models of massive stars ranges between 13 and $120M_{\odot}$ in mass, between $[\text{Fe}/\text{H}]=-3$ and 0 in Fe abundance. In addition to the non rotating models, two initial rotation velocities have been considered: 150 and 300 km/s. A detailed description of the input physics and the assumptions adopted in these computations are discussed in our paper ⁶⁾. Figure 21 in that paper summarizes the ξ values that we obtain for our grid as a function of the initial mass. The grey area marks the region that corresponds to the models that fully collapse in the remnant. According to the ξ parameter, only models less massive than $\sim 40M_{\odot}$ should produce a successful explosion. But there is another constraint the models must satisfy in order to represent *real* explosions. From the analysis of the available data about the kinetic energies of the Type II Plateau supernovae detected, it has been discovered ⁷⁾ that there are no observed Type II Plateau supernovae with kinetic energies of the ejecta in excess of 3 FOEs. If we take into account also this constraint, our models more massive that $25M_{\odot}$ should fully collapse in the remnant.

The net result of this analysis is shown in Figure 36 of our paper, where

the masses of the remnants for the various masses, metallicities and initial rotation velocities are shown. The Figure shows that in order to get black hole masses in excess of $30M_{\odot}$ or so it is necessary to have both a low initial metallicity (so to minimize the efficiency of the mass loss) and a low initial rotation velocity (otherwise the stars would largely overcome their Eddington luminosity and would lose a large amount of mass even at very low metallicities). The interested reader will find all the details about our latest extended grid of models in our paper ⁶).

References

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