PINPOINTING THE FORMATION OF THE REVERSE SHOCK

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The reverse shock in supernova remnants is a key factor in the destruction of newly formed dust in the ejecta, with its destructiveness highly dependent on its speed and the ejecta density. Accurate estimation of the supernova dust budget requires understanding the formation and evolution of the reverse shock. Traditional models, like the one by Truelove & McKee (1999) [1], assume initial conditions for the ejecta independent of the interstellar medium (ISM) properties, leading to assumptions that a reverse shock will always form. However, reverse shock formation is actually contingent on the ISM conditions. Most numerical studies rely on these traditional models, which may result in unreliable outcomes. This work proposes a new analytical solution based on the physical parameters of the supernova explosion and the surrounding medium, offering a more realistic prediction of reverse shock formation and evolution, thereby improving the accuracy and comparability of simulations to observations.

EVOLUTION OF A SUPERNOVA SHOCK

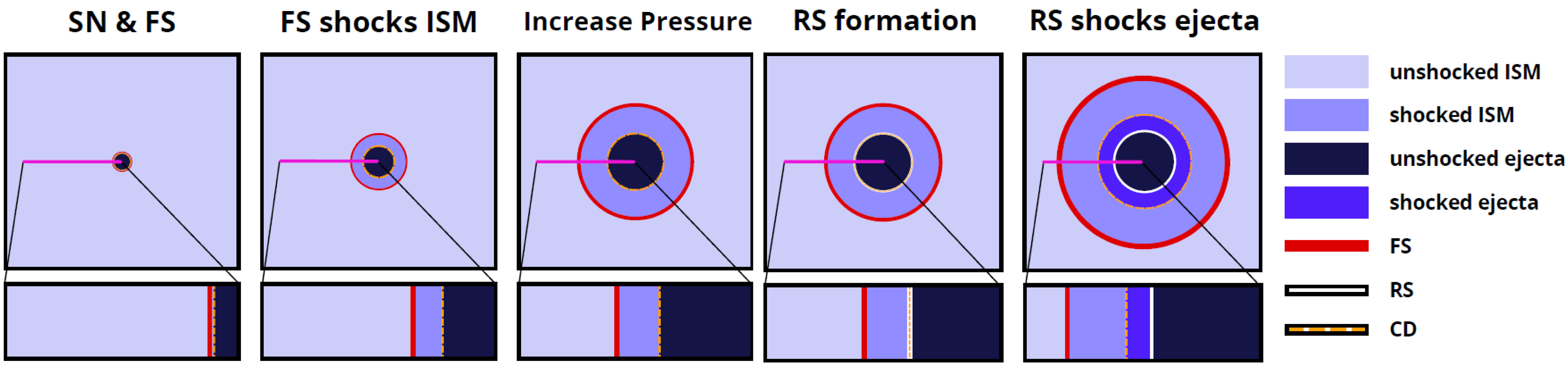


Fig1. The evolution of a spherically symmetric supernova. It shows the distinct phases the supernova goes through from the explosion which occurs simultaneously to the creation of the forward shock to the formation of the reverse shock.

The reverse shock formation depends on the pressure balance between the shocked ISM and the unshocked ejecta. Initially, the pressure of the shocked ISM is not high enough to create a reverse shock. As the forward shock processes more and more ISM gas, a shell of shocked ISM material is formed. This shell faces pressure from the (unshocked) ejecta and must accommodate the increasing amounts of gas crossing the forward shock. As the supernova expands the pressure of the shocked shell increases over time relative to the ejecta pressure and only when the shell pressure exceeds the ejecta pressure will a reverse shock form.

TRUELOVE AND MCKEE MODEL

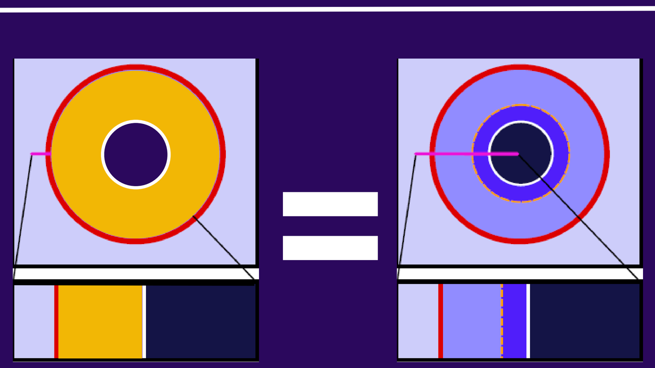
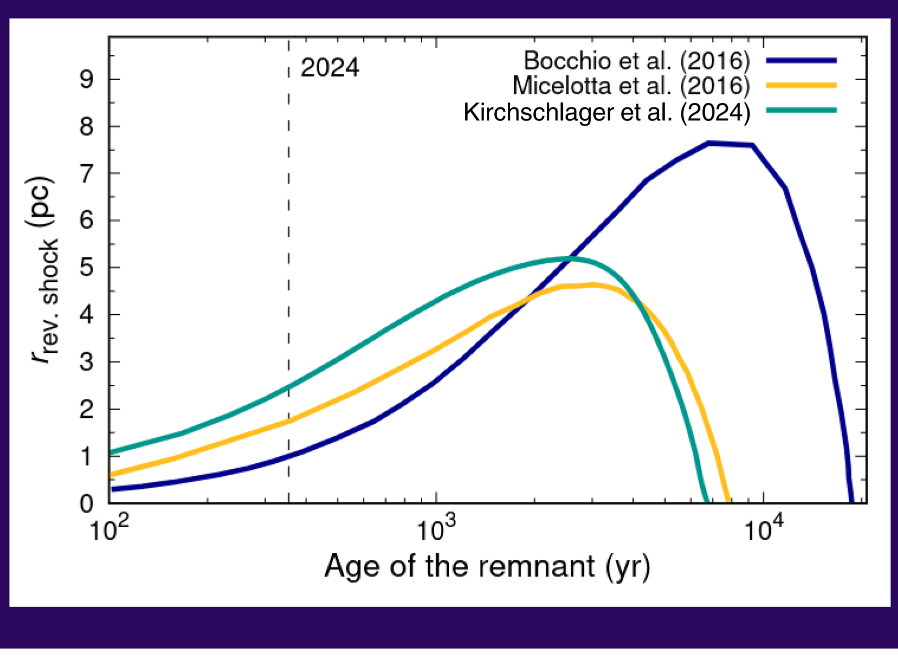


Fig. 2: Comparison of the initial conditions assumed in the Truelove and McKee analytical solution to the simplified evolution of a supernova presented in Fig. 1.

The initial conditions of the Truelove and McKee model are shown in the left plot. This model assumes the ejecta consists of an envelope (yellow) and a core (dark blue) region. The high pressure in the envelope region forces the immediate formation of a reverse shock. However, when compared to the last panel of Fig. 1 (right plot), it is evident that this model fails to account for the shocked interstellar medium (ISM). Moreover, the time of formation of the reverse shock does not accommodate scenarios where a reverse shock may never form.

Furthermore, the velocity distribution in the envelope is assumed to be a polynomial with an index 'n'. This index is not derived from the properties of the supernova and is usually chosen based on what fits observations best. However, this does not guarantee that the past or future evolution of the reverse shock will be well described by the model, and different 'n' can lead to different evolutionary paths (Fig 3).

Fig. 3: Different evolution of the reverse shock for Cas A for works using very similar initial conditions. The yellow and green lines use the same 'n' index but the former assumes a density in the ISM that decreases with the square distance from the explosion. Blue and green lines vary only in the adopted n value. One can see that this creates a large difference in results. Modified from [2].



NEW MODEL FOR EARLY SN EVOLUTION

In our new model, we calculate the exact moment of formation of the reverse shock and eliminate the need to assume a velocity distribution for an envelope region. Therefore our model relies solely on the properties of the supernova explosion (explosion energy and ejecta mass) and ISM fluid properties (density and temperature).

In Figure 4 we show the point when the pressure of the shocked ISM reaches the same value as the pressure of the ejecta, after which the reverse shock will form.

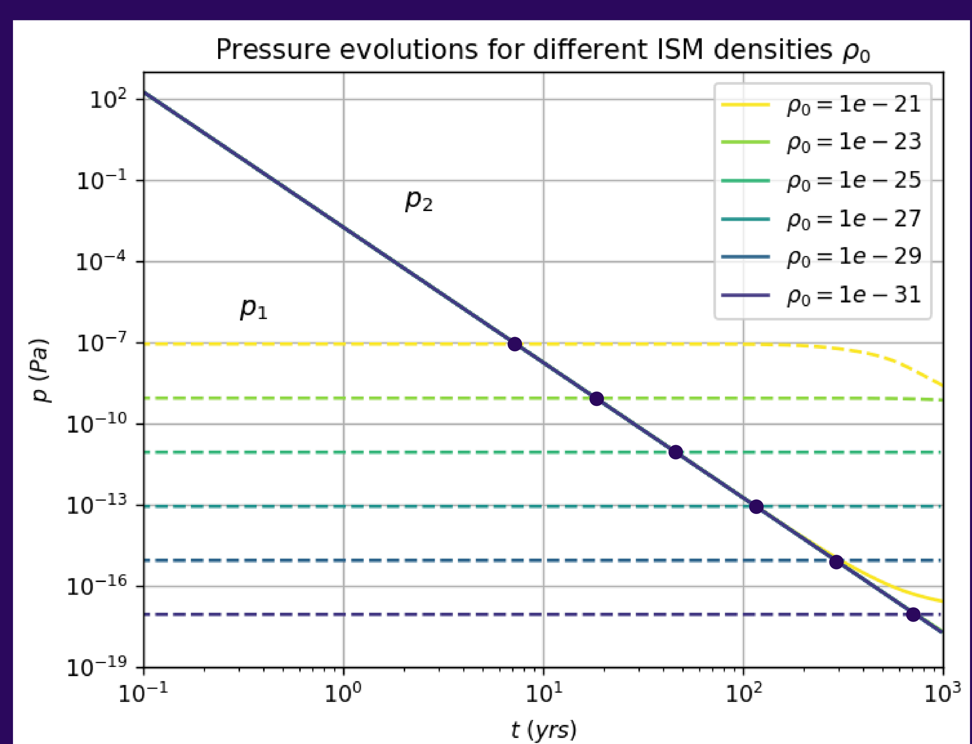


Fig. 4: Evolution of the pressure in the shocked ISM shell (P1) and the ejecta (P2) for different ISM densities (in SI units). Pressure equilibrium points are shown by bullet points.

(10^{-21} kg/m^3 ~ 1 H atom/cm^3)

The lower the density of the ISM the longer it will take for the reverse shock to form. The longer it takes the reverse shock to form the lower the density of the ejecta it will find and the lower its velocity will be, thus leading to less dust destruction [2]. For SN 1987A ISM densities this gives a time for the reverse shock of around 20 years which is consistent with observations.

CONCLUSIONS

- The reverse shock formation time will depend on the conditions of the ISM. The denser the gas surrounding the supernova explosion the faster the shock will form.
- The evolution of the reverse shock in this new analytical model can be derived solely from ISM conditions and properties of the SN explosion, offering an improvement over the Truelove and McKee model.

RELATED LITERATURE

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