New self-similar solutions in cooling supernova remnants

A. Gintrand[1,2], S.E. Bouquet[1,2], C. Michaut[2]

[1] *CEA, DAM, DIF, F-91297, Arpajon, France*
[2] *Laboratoire Univers et THéories (LUTH), Observatoire de Paris, CNRS, F-92195 Meudon, France*

At the end of a massive star life (typically more than 5 to 6 solar masses), the star becomes a supernova. After the explosion, the strong shock begins to propagate with the ejecta of the star in the circumstellar medium and later in the interstellar medium. This object is called a supernova remnant (SNR). During its expansion, the SNR accumulates matter behind the shock front to form a shell. Theory describes three phases of the SNR. The first phase corresponds to a ballistic expansion with a radius R of the SNR proportional to the age t of the SNR. In the second stage, called the Sedov-Taylor regime [1], the evolution is adiabatic (energy conservation) and R increases like $R \propto t^{2/5}$. In this work we study the last stage (radiative regime) where the SNR energy is not anymore preserved. Indeed, the SNR begins to lose energy by radiation cooling so the expansion is more decelerated than in the adiabatic evolution. According to previous modelling, $R \propto t^n$ where the exponent n satisfies $n < 2/5$ [2,3,4]. In this study, we take the dynamics of the SNR and its cooling in a consistent way. Including losses in the energy equation, we derive new self-similar solutions (SSS) describing the 1D inner structure of the SNR together with its radius according to the magnitude and spatial dependence of the cooling rate. These new solutions are of “second kind” [5] meaning that we need to solve a non linear eigenvalue problem to find the SSS. The exponent n decreases when the total radiative losses increase. Moreover, it turns out that specific cooling configurations would be subject to the Rayleigh-Taylor instability (RTI). These results will help to interpret recent simulations carried out by Badjin et al. [6] that highlighted the presence of such instabilities developing during the thin shell formation by using more realistic cooling processes with opacity tables. This RTI could explain the filamentation of old SNR and would occur before the development of the further Vishniac instability [7,8,9,10].

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