The Effect of Circumstellar Medium on Cosmic Ray Acceleration in Type Ia Supernovae

Dimitrios Kantzas[1,†], Alexandros Chiotellis[2] & Apostolos Mastichiadis[1]

[1] Department of Physics, University of Athens, 15783 Zografos, Greece

[2] I.A.A.S.A.R.S., National Observatory of Athens, 15236 Athens, Greece

1. Abstract

We present our results on the range and time evolution of the maximum energy that charged particles can obtain while they are accelerated in the forward shock of Supernova Remnants resulting by Type Ia Supernovae (SNe Ia). In particular, based on semi-analytical and numerical descriptions, we investigate the dynamics of a Supernova Remnant evolving in a modified ambient medium formed by the mass outflows of the progenitor system. We associate the ambient medium properties to the suggested diversity of SNe Ia progenitors and we study the effects of such an evolution on the acceleration of cosmic rays (CRs). We find that the range and the time evolution of the cosmic rays' maximum energy are strongly dependent on the ambient medium properties. Thus, combining this result with the fact that a large percentage of of SNe Ia seem to interact with the circumstellar structures (Stenberg et al., 2011 [1]), we conclude that the modification of the ambient medium by the SN Ia progenitors cannot be neglected in the study on the origin of galactic cosmic rays.

2. SNe Ia Dynamics

SN EJECTA AND AMBIENT MEDIUM

There are two characteristic quantities that are taken into consideration while studying the dynamics of a SN:

- the density distribution of the upstream medium (ρ_{up}) which can be generally described as: $\rho_{up} \propto R^{-s}$ where R is the radius from the explosion centre and $s = constant$,
- the density structure of the SN ejecta (ρ_{ej}). Here we consider a power law: $\rho_{ej} \propto R^{-n}$ with $n = 7$.

We assume two characteristic cases for the upstream medium around SNe Ia:

i) **ISM** with $s = 0$ and density $n \simeq 1\ cm^{-3}$

ii) **CSM** upstream medium modified by the following stellar wind emanating from the progenitor system:

- **AGB** -Asymptotic Giant Branch star with $s = 2$, $dM/dt = 10^{-5}\ M_{\odot}/yr$ and $v_w = 10\ km/sec$,
- **RG** -Red Giant with $s = 2$, $dM/dt = 10^{-7}\ M_{\odot}/yr$ and $v_w = 70\ km/sec$,
- **WD** -White Dwarf with $s = 2$, $dM/dt = 10^{-7}\ M_{\odot}/yr$ and $v_w = 10^3\ km/sec$

with dM/dt the mass loss rate and v_w the wind terminal velocity.

SN Ia DYNAMICS

Analytical

Based on the semi-analytical approach for the evolution of a SN made by [2], we can export:

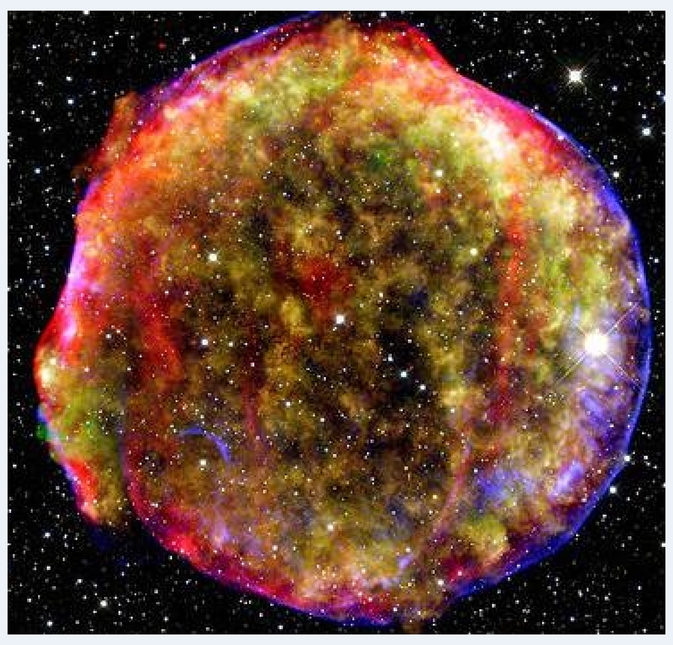
- the radius $R \propto t^{(n-3)/(n-s)}$ of the SN,
- the velocity $v_{sh}(t) = \dfrac{dR}{dt}$ of the expansion.

Numerical

We use the numerical code designed by Keppens et al. in 2003 [3] which provides us with the evolution of a SN, i.e. $R(t)$ and $v_{sh}(t) = dR/dt$.

3. CRs Maximum Energy

In order to find the maximum energy $E_{max}(t)$ of a single particle accelerated in a SN, we need:



- $R(t)$ and $v_{sh}(t)$ – the radius and the velocity of the expansion, respectively
- $l = D/v_{sh}$ – the particle's mean free path with D the diffusion coefficient
- ζ – the fraction of the $R(t)$ where the particle escapes from the source, i.e. when $l_{esc} = \zeta R(t)$

We assume that the magnetic field of the source is amplified by a factor:

- $\xi_B \rho_{up} v_{sh}^2 = B^2/8\pi$, with $\xi_B = 0.05 - 3.5\%$ (see Vink 2008 [4] and references therein)

and according to Cristofari et al. 2013 [5], we express the magnetic field of the downstream area and the diffusion coefficient as:

$$B_{down} = \sigma B_o \sqrt{1 + \left(\frac{v_{sh}}{v_d}\right)^2} \quad \& \quad D = D_{Bohm}\left[1 + \left(\frac{v_d}{v_{sh}}\right)^2\right]^3 \qquad (1)$$

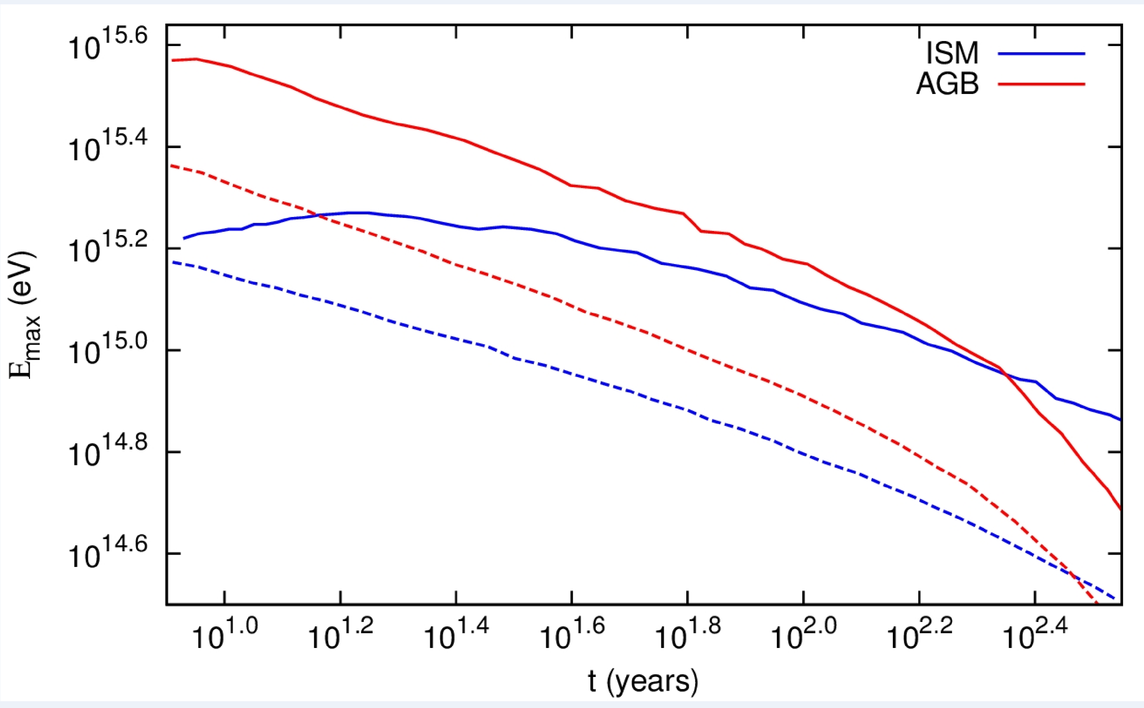
- σ – the shock compression ratio and B_o – the value of the magnetic field before the amplification
- $v_d = \sqrt{\sigma^2 B_o^2 / 8\pi \xi_B \rho_{up}}$ – a normalization for the velocity which points out when the amplified magnetic field starts to damp
- $D_{Bohm} = Ec/3eB$ – the Bohm diffusion coefficient with E the particle's energy

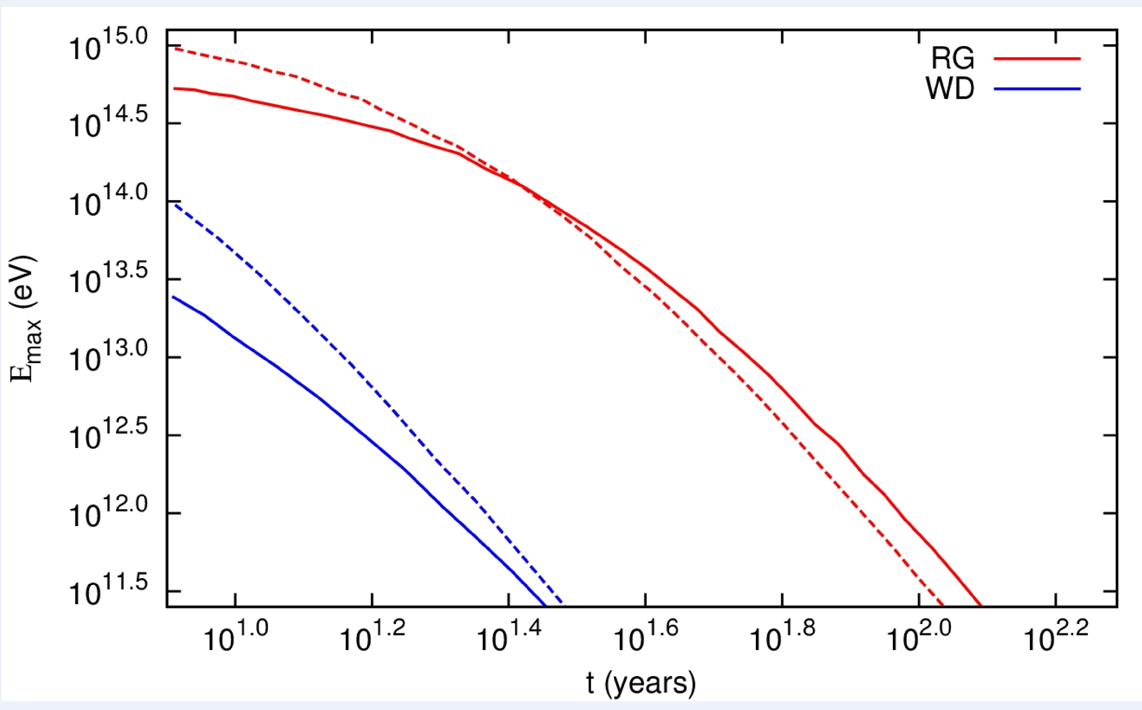
Combining these expressions, we get that the maximum energy of the particles can be written as:

$$E_{max}(t) = \frac{3\zeta e}{c}\sigma B_o R(t) v_{sh}(t) \sqrt{1 + \left(\frac{v_{sh}(t)}{v_d}\right)^2}\left[1 + \left(\frac{v_d}{v_{sh}(t)}\right)^2\right]^{-3} \qquad (2)$$

4. Results

Based on the above description we estimate -both **analytically (dashed line)** and **numerically (solid line)**- the time evolution of the maximum CR energy for the studied cases presented in Section 2. The results are illustrated in the following plots where it has been used: $\zeta = 0.1$, $\xi_B = 0.05$, $\sigma = 6$ and $B_0 = 1\ \mu G$.





5. Conclusion

- The maximum energy of the Cosmic Rays can be attained during the free expansion phase and especially during the very first times after the breakout. Thus, it is incorrect to assume that the maximum energy can be attained during the transition between the free expansion and the Sedov-Taylor phase as is widely believed.
- The SN Ia surrounding medium properties play a vital role in the range and time evolution of CR maximum energy. This combined with the fact that an increasing, non-negligible number of SNe Ia seem to interact with circumstellar structures, leads to the conclusion that neglecting the ambient medium modification around SNe Ia could lead to substantial errors on the estimations of the Galactic CR properties and origin.
- We intend to include different ejecta density profiles e.g. steeper (in particular $n = 12$) or exponential in a future work.

6. References

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† dimitrisk07@hotmail.com