Acceleration of Cosmic Rays in Supernova–Remnants

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1 Introduction

It is commonly accepted that supernova-explosions are the dominant source of cosmic rays up to an energy of 10^{14} eV/nucleon (1). Moreover, these high energy particles provide a major contribution to the energy density of the interstellar medium (ISM) and should therefore be included in calculations of interstellar dynamic phenomena. For the following we will consider the first order Fermi mechanism in shock waves to be the main acceleration mechanism. The influence of this process is twofold; first, if the process is efficient (and in fact this is the case) it will modify the dynamics and evolution of a supernova-remnant (SNR), and secondly, the existence of a significant high energy component changes the overall picture of the ISM. The complexity of the underlying physics has prevented detailed investigations of the full non-linear selfconsistent problem. For example, in the context of the energy balance of the ISM it has not been investigated how much energy of a SN-explosion can be transfered to cosmic rays in a time-dependent selfconsistent model. Nevertheless, a lot of progress has been made on many aspects of the acceleration mechanism and we refer to recent reviews for more details (2,3).

2 Basic physics, initial conditions and method of solution

We apply the usual system of time-dependent hydrodynamical equations to the problem and include an additional cosmic ray pressure term ∇P_C in the momentum equation to describe the reaction on the fluid. The high energy particles are treated in the hydrodynamical approximation as a relativistic gas with adiabatic index $\gamma_C = 4/3$. We note that in this approximation the particle distribution function $f(p)$ is 'averged' out. Hence, it is impossible to determine the mean cosmic ray diffusion coefficient $\bar{\kappa}$ and γ_C in a selfconsistent way from $f(p)$. However, the system of equations is closed and consistent if one specifies $\bar{\kappa}$, γ_C and an equation of state for the gas as functions of the other used quantities. For the later we use the ideal gas law with $\gamma_G = 5/3$. Therefore all effects of cooling and heating are ignored. The diffusion coefficient is taken to be constant throughout, $\bar{\kappa} = 10^{27}\,\mathrm{cm}^2\mathrm{sec}^{-1}$.

For the SN-progenitor star we use a very simple model. The stellar density is taken to be constant at $10^{-11}\,\mathrm{g\,cm}^{-3}$ out to a radius of $5 \cdot 10^{14}$ cm and decreases than exponentially with a scale length of 10^{14} cm until the density of the external medium is reached, $\rho_{ext} = 5 \cdot 10^{-25}\,\mathrm{g\,cm}^{-3}$. The SN-energy of 10^{51} ergs is deposited purely as thermal energy within 10^{13} cm. The ejected mass corresponds to 5 $M_\odot$. The external medium is initially at rest and at a temperature $T_{ext} = 8000$ K. The exact details of the progenitor are probably not so critical for the subsequent evolution. More serious is the possibility that a stellar wind from the SN-progenitor star may modify the evolution of the SNR by producing a density structure in the surrounding medium; for this first calculation we have ignored this effect. In the homogeneous external medium the cosmic ray pressure is assumed to be equal to the gas pressure.

The system of equations is discretized and solved numerically on a fully adaptive grid (4). Technically speaking we use a first order upwind conservative implicit scheme thus ensuring the global conservation of mass, momentum and energy. An additional equation for the distribution of grid points is solved simultanously with the physical equations. This procedure enables us to resolve and follow the nonlinear waves over 10 orders of magnitude in radius. The maximum resolution corresponds to 10^8 points and is needed to handle the strong shocks arising in the problem.

3 Results

Between $t = 3 \cdot 10^6$ sec and $t = 10^{11}$ sec the flow structure is characterized by a strong forward shock in the ISM. A contact discontinuity separates the stellar ejecta from the external material and the reverse shock is advected outwards during this phase. The interior background gas cools down adiabatically whereas the cosmic ray pressure stays more or less constant because the adiabatic decompression is compensated by a diffusive flux of particles from the external medium into the remnant. Assuming a mean velocity $v = 10^8 \mathrm{cm\,sec}^{-1}$ the typical length scale of diffusion is $l_d = \frac{\kappa}{v} = 10^{19}$ cm and within this radius diffusion will lead to a flat cosmic ray pressure. Figure 1 depicts the physical variables at time $t = 6.4 \cdot 10^9$ sec and every gridpoint is plotted individually to demonstrate the achieved resolution in this calculation.

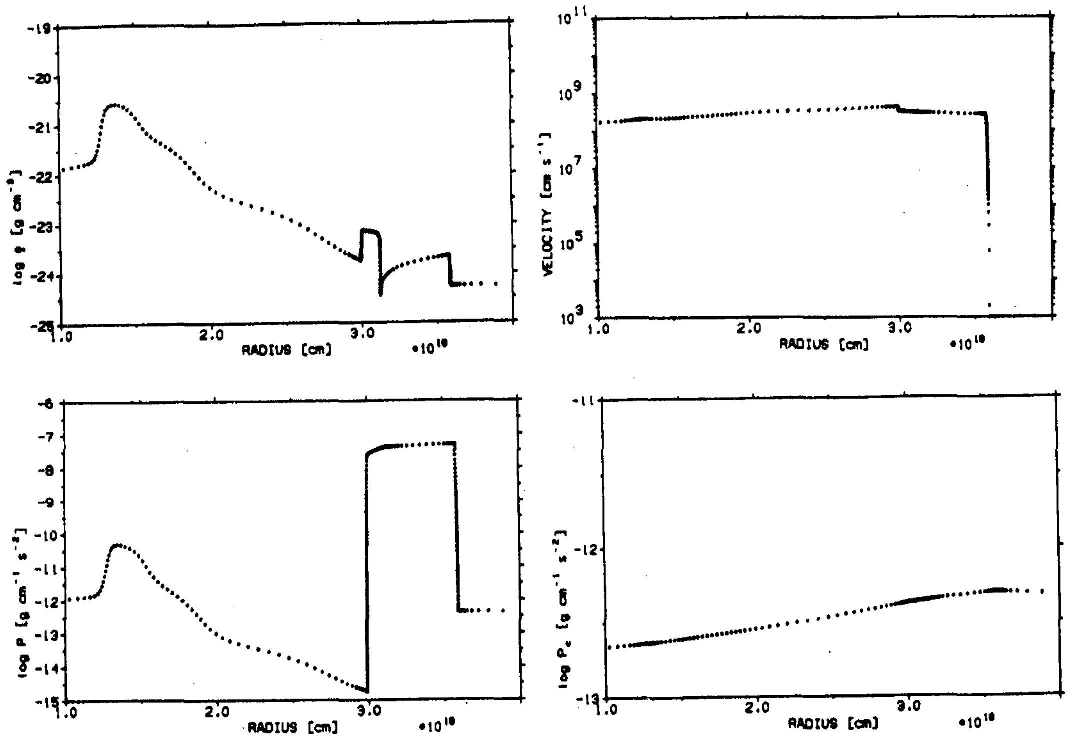

Figure 1:— Physical variables between 10^{14} and $4 \cdot 10^{14}$ cm at time $t = 6.4 \cdot 10^9$ sec. The forward shock, contact discontinuity and reverse shock can be seen.

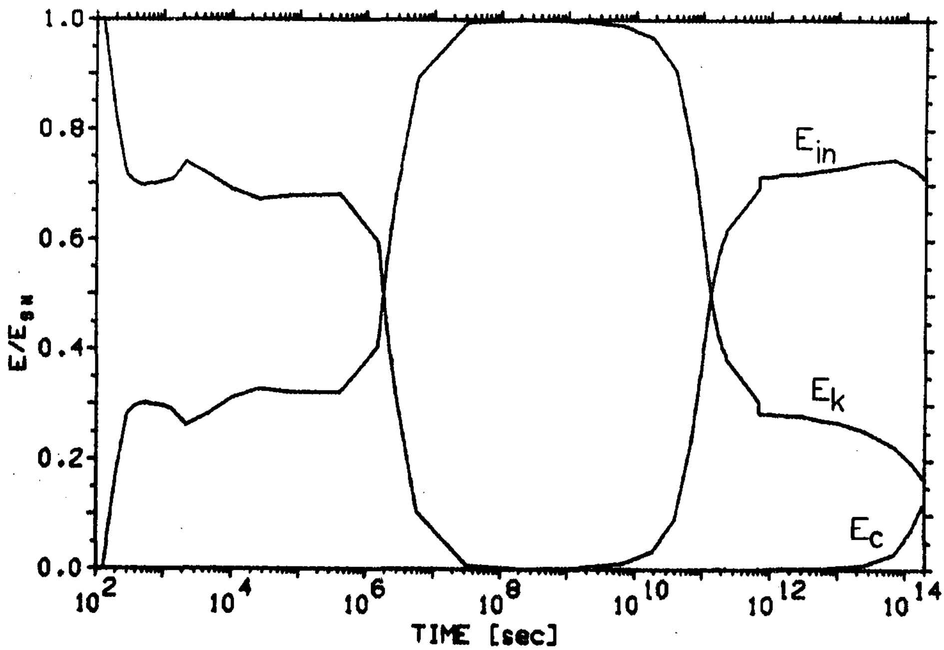

Figure 2:— Energy partition between internal gas energy, E_{in}, kinetic energy, E_{k} and cosmic ray energy E_{c} throughout the evolution of the SNR.

At a radius of about $2 \cdot 10^{19}$ cm and at a time $t = 1.3 \cdot 10^{11}$ sec the ejected mass becomes comparable to the swept-up mass. This terminates the phase of free expansion, the flow is decelerated and the reverse shock starts propagating inwards. The ingoing reverse shock accelerates in running down the large density gradient in the interior of the SNR. The strengthening of the reverse shock is further enhanced by the geometrical focusing and the flow velocities become formally superluminal (in this Newtonian formulation). The very low density gas is heated up to extreme temperatures of $T \approx 10^{10}$ K and the dominant force in the interior is now again the gas pressure. The very high Mach-number of 10^6 yields a very high efficiency in accelerating cosmic rays but the small radius 10^{15} cm compared to the actual SNR-radius of $4 \cdot 10^{19}$ cm results in a very small fraction of the total cosmic ray energy being associated with this phenomenon (*c.f.* Fig. 2). A reflecting boundary condition is imposed at an inner radius of 10^{11} cm, and so the inward running shock wave reflects there, propagates outwards and is again reflected at the contact discontinuity. A second somewhat weaker reverse shock compresses and heats up the interior again. During this phase the outer shock continues to expand into the ISM and the interior of the remnant is adiabatically decompressed.

After these events the further evolution corresponds to the Sedov-phase, where an almost homogeneous high pressure bubble expands into the external medium. The Mach-number of the outer shock is moderate, $M = 10 \ldots 1$. The major contribution to the particle acceleration occurs during this phase, $t \geq 6 \cdot 10^{11}$ sec. The time-dependence of the different energy components is shown in Figure 2. Three phases can be distinguished easily, first the shock wave running through the star, secondly the phase of free expansion with most of the energy stored in kinetic energy and thirdly, after the violence of the ingoing reverse shock waves, the Sedov-phase where the SN-energy is partly given to cosmic rays. As a main physical result we can state that in this selfconsistent model and for the adopted parameter of $\bar{\kappa} = 10^{27}\,\mathrm{cm}^2\mathrm{sec}^{-1}$ and for times $t = 2 \cdot 10^{14}$ sec about 12% of the SN-energy is transferred to high energy particles.

4 Discussion

The main unknown parameter in this problem is the mean diffusion coefficient $\bar{\kappa}$. In this calculation we have used a constant value of $10^{27}\mathrm{cm}^2\mathrm{sec}^{-1}$ whereas in reality $\bar{\kappa}$ is expected to be both time- and radius dependent. This value is almost certainly too large so that we have if anything underestimated the particle acceleration efficiency. Unfortunately calculations with smaller values of $\bar{\kappa}$ encounter difficulties which we attribute to a cosmic ray driven instability (see paper OG 8.1–5) and which inhibit a detailed description of the further evolution of the remnant. The assumed constancy of the external cosmic ray pressure is another restriction which will influence the net energy gain of cosmic rays. A stellar wind from the progenitor star can decrease the external cosmic ray pressure and in this case the SN will explode in a more or less cosmic ray pressureless environment. Due to our hydrodynamical description of the high energy particles we have not addressed the difficult question of injection of particles at the shock.

5 Conclusions

This numerical investigation demonstrates for the first time that a SN-explosion can transfer a significant part of its energy to cosmic rays. The obtained value of about 12%, probably an underestimate, is in general agreement with current estimates of the efficiency needed to replenish the observed cosmic ray energy density.

References

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