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THE GALACTIC ORIGIN OF COSMIC RAYS I

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ABSTRACT

The theoretical basis for the supernova envelope shock origin of cosmic rays is reviewed. The theoretical explanation of the SN Type I light curve requires the ejection of a relativistic mass fraction. The criterion of the adiabatic deceller-ation by Alfvén wave trapping neither applies in theory, when $\beta > 1$, or practice, the Starfish high altitude nuclear explosion experiment. Arguments of delayed acceleration due to K-capture are not applicable to SN ejecta because a period of prompt recombination exists before subsequent stripping in propagation.

1. Introduction

The question of the origin of cosmic rays has received enthusiastic attention in recent years with the popularization of the original suggestion (Schatzman 1963) of stochaistic acceleration of particles across hydrodynamic shock fronts. Bell (1978); Axford, Leer, and Skadron (1977); and Blanford and Ostriker (1978, 1980) have recently shown that under limited circumstances a universal power law is obtained for the accelerated particle spectrum dependent upon the shock compression ratio. The general awareness of the phenomena is recent, and few objections have appeared. Eichler (1980) has pointed out a restrictive condition for initial injection of particles for acceleration; namely, that the accelerated particles must originate from an in situ distribution. Here we offer another objection concerning enhanced CR diffusion velocity ahead of the shock when the CR pressure exceeds $B^2/8\pi$ ($\beta > 1$). By contrast the concept of the acceleration by supernova envelope shock acceleration has been around for a long time (Colgate and Johnson 1960; Colgate and White 1966) and has received its share of criticisms. In this paper I would like to review several of these criticisms with particular emphasis upon adiabatic decelleration. I would like to emphasise that this still is the only theory that predicts the generation of the whole cosmic ray spectrum from low energy out to the highest energies of $\geq 10^{20}$ eV by a single monotonic mechanism.

2. Possible Evidence of Relativistic Acceleration

There is now weak evidence of relativistic expansion from the interpretation of the supernova Type I light curve. The most reasonable interpretation of the classical 54 to 56 day exponential optical decay is due to the progressive transparency of the mantle to ($Co^{56} \rightarrow Fe^{56}$ 77d, 20%) β^{+} energy deposition (Colgate, Petschek, and Kriese 1980). This interpretation absolutely requires the radial combing of any in situ magnetic field no matter how small $\gtrsim 10^{-4}$ of typical white dwarf values. To be effective, this radially combed magnetic field must advance ahead of the principal mass of ejecta at near the speed of light. The only current alternative explanation is the emission of a very large flux of far infrared (20 microns) radiation (Axelrod et al 1980).

3 Spectrum from Shock Acceleration

The power loss spectrum of ejected matter $(N > E) \propto E^{-\Gamma}$, $\Gamma \cong 1.58$ theoretically) has been calculated analytically by Colgate and Johnson (1960) Johnson and McKee (1971), Eltgroth (1971 and 1972) and numerically by Colgate and White (1966) (nonrelativistically) and relativistically by McKee and Colgate (1973); Colgate, McKee, and Blivens (1972); and by Shapiro (1979). The effect of radiation transport in the relativistic frame has been treated by Colgate and Petschek (1979) and Glaviano and Raymon (1981). I do not believe that any serious inconsistency exists among these multiple theoretical treatments.

4. Nuclear Composition

An outline of a theory of the preservation of nuclear species through the shock transition by electron positron pair dyanmic friction is given in Colgate (1974). The high energy, $\gtrsim 10^{15}$ eV, part of the spectrum was similarly considered in the same publication arising from the shock propagation in the magnitosphere of the presupernova star.

Composition is most likely determined by the nuclear composition of the binary accreted outer white dwarf surface layer (Type I supernova) of mass fraction 10^{-5}. This near normal composition matter lies outside the helium burning zone (10^{-4} mass fraction). After shock acceleration and post shock expansion ($\lesssim 1$ s) the matter is cold and has recombined with its electrons. Arguments concerning delayed acceleration following K-capture in Co^{57} etc. by Cassé and Meyer (1978) and Tueller et al (1979) do not apply to this matter that either can have undergone K-capture in the distant past or following some shock-induced nuclear synthesis and subsequent acceleration, then as neutral atoms.

5. Diamagnetic Bubble

The most serious criticism of the theory is that the ejected cosmic-ray matter merely blows an adiabatic hole in the interstellar medium trapping all the high-energy particles by induced Alfvén waves.

The energy is given up to the ISM and no cosmic rays are produced (Kurlsrud and Zweibel 1975).

My own experimental experience was that for whatever reason, the perfect degree of trapping was highly unlikely to occur in practice, most likely because of the particle pressure and velocity distribution function. In the one most dramatic man-made case, the detonation of a high altitude (above the earth's atmosphere) nuclear bomb ("Starfish" event) resulted in negligible debris trapping in the earth's magnetic field. (D'Arcy and Colgate 1965). Here a megaton equivalent nuclear explosion blew a diamagnetic bubble in the earth's field ≅ 400 km in diameter. The debris ($\gtrsim \frac{1}{4}$) escaped the bubble promptly and traversed to the conjugate point 10^4 km away at a velocity (≅10^8 cm s^{-1}) corresponding to its original kinetic energy. The mass and arrival time were recognized from its radioactive gamma rays. The criterion of Alfvén wave trapping is well satisfied since the typical bomb debris ions, ≅ 10 fold ionized, had a Larmor radius of $\lesssim$ 10 km and a path length along the field of 10^3 times this. The Alfvén velocity in the medium was ≅ 6 × 10^6 cm s^{-1} compared to the debris velocity of 10^8 cm s^{-1}. On the basis of the Kulsrud-Zweibel trapping theory, the Alfvén wave growth rate should have been close to the cyclotron frequency of 100 Hz compared to a transit times of 10 s.

Even a small Alfvén wave turbulence should have increased the perpendicular component of the largely parallel going debris so that it would have mirrored either in the bubble magnetic mirror (trapping), or by a secondary one at the conjugate point (mirror reflection). The fact that no trapping or reflection occurred in this case is strong evidence that a significant fraction of high energy matter (cosmic rays) could escape a diamagnetic bubble in the ISM. One notes that escape of the debris in the Starfish event occurred when the size of the bubble encompassed a mass equal to the debris, not a magnetic energy (≅ 1/20) of the debris kinetic energy.

A further theoretical argument to the same effect is offered by the analysis of Holman, Ionson, and Scott (1979) who point out that the Alfvén wave limit to streaming is violated if the particle pressure exceeds the magnetic field pressure. This is certainly the case for a typical ejecta energy of 10^{49} ergs that must expand to ≅ 50 pc before the criteria is satisfied. By this time the expansion velocity due to the cosmic rays alone would be the Alfvén velocity of the medium 10^6 to 10^7 cm s^{-1}, but slower ejecta with more mass will maintain an expansion velocity of ≅ 10^8 cm s^{-1}, and compress any cosmic rays trapped between the slower massive ejecta and the shock front in the ISM. There will, therefore, be a time for the cosmic ray fraction to escape by streaming along the field lines that is longer than the expansion time of the bubble by the ratio $(c/v_{expansion}) \cong 10^3$, provided free streaming at $\beta > 1$ is allowed ($\beta = CR_{energy}/(B^2/8\pi)$). This is grossly longer than required. Instead, we expect the cosmic rays to escape when the cosmic ray mass fraction runs into an equal mass of ISM just as in the Starfish event case. This occurs at a radius, $R_{CR\,escape} \cong (10^{-5} M_\odot A/n_p)^{1/3} \cong 2 \times 10^{17} (n_p^{-1/3})$ cm or after a year from the explosion time, n_p ≅ proton density of the ISM. This is the time when the cosmic ray ejecta interacts most strongly with the ISM, i.e., an equal mass collision and where those particles whose direction relative to the field is other than perpendicular will be directed along field lines. This same criteria of super Alfvén speed streaming can be applied to the theory of shock acceleration of cosmic rays in the ISM. We do so in a companion paper where we discuss the limitation to ISM shock acceleration if the pressure of the comic ray particles ahead of the shock exceeds the magnetic field pressure.

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