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THE ORIGIN OF COSMIC RAYS. III. PARTICLE ACCELERATION BY GLOBAL SPIRAL SHOCKS

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ABSTRACT

Cosmic-ray acceleration by global spiral shocks in galactic disks is investigated using existing theory. The diffusive shock acceleration (DSA) mechanism is discussed in the low-velocity regime represented by density wave shocks. It is found that a medium of $T \approx 10^4$ K, partially to fully ionized, supports the DSA mechanism. It is concluded that existing theory permits particle acceleration by global, slow moving shocks as suggested by observational work on the spiral galaxy NGC 3310.

Subject headings: cosmic rays: general — galaxies: individual — galaxies: structure — particle acceleration — radio sources: galaxies — shock waves

I. INTRODUCTION

In a follow-up to the observational work of Duric *et al.* (1986, hereafter Paper I) and Duric (1986, hereafter Paper II) we present the third in a series of papers addressing the problem of the origin of cosmic rays in spiral galaxies. In the previous papers it was reported that cosmic rays appear to originate in the spiral arms of the test galaxy NGC 3310 and that density wave shocks may be accelerating particles to cosmic-ray energies. The aim of this paper is to determine whether existing theory on particle acceleration by shocks is compatible with the relatively slow density wave shocks. In particular, the ability of density wave shocks to accelerate electrons to a few GeV (the radio synchrotron window) is investigated using standard theory. The necessary conditions for the formation of global shocks are briefly reviewed, and the further conditions for particle acceleration by these shocks is discussed.

Typical shock velocities predicted by density wave theory lie in the range of 20–100 km s^{-1}, and, consequently, a significant fraction of the ISM must have a sound speed lower than these values, in order for supersonic shocks to form. In the context of the three-phase model of the ISM (McKee and Ostriker 1978) this condition is violated for the hot component (10^6 K). For example, if $n \approx 0.01$ cm^{-3} and $T \approx 10^6$ K, the sound speed is ~ 100 km s^{-1} and the shocks are not supersonic and, therefore, do not significantly affect the ISM. It is not clear, though, whether the hot phase dominates galactic disk dynamics. Mathewson, van der Kruit, and Brouw (1972) have demonstrated the existence of global shocks in M51, and the existence of narrow dust lanes along the inside edges of spiral arms has been demonstrated for a number of spiral galaxies (e.g., Lynds 1974). Recent work by Ku, Kahn, and Pisarski (1984) on the Cygnus loop in our own Galaxy suggests that it is immersed in a 10^4 K gas. In addition, the observed shock velocity is ~ 100 km s^{-1}, proof enough that slow shocks do exist in the ISM. Furthermore, Bell (1978*a*, *b*) argues that the Cygnus Loop shocks may be accelerating particles to cosmic-ray energies, and Bhat *et al.* (1985) suggest the same for the Loop 1 remnant based on γ-ray observations. We therefore proceed with the assumption that the hot component does not inhibit or significantly affect the shock dynamics.

II. MODELING SPIRAL SHOCKS

Within the context of the classical density wave theory (Lin and Shu 1964), the shock velocity may be expressed as

$$v_s = [\Omega_g(r) - \Omega_p]r \sin i(r) + \delta(r) , \quad (1)$$

where Ω_g and Ω_p are the angular velocities of the disk and spiral pattern, respectively, and where the spiral pattern is assumed to have a constant angular velocity. The pitch angle of the spiral arms is given by $i(r)$, and $\delta(r)$ corrects for the effects of spiral arm self-gravity and noncircular gas motions. The latter is generally of the order of 10 km s^{-1} (Roberts 1969) and can be neglected for spiral galaxies with open arms and therefore greater shock velocities. Is the density wave theory an adequate model for this kind of study and is the equation given above an adequate representation of the kinematics? We briefly discuss this question below.

The major weaknesses of the density wave theory are that (i) in isolated galaxies there are often no obvious driving mechanisms, and (ii) nonlinear wave effects are not taken into account. Toomre (1977) uses the concept of swing amplification to avoid these difficulties. In the Toomre models, the pattern speed rotates differentially but often at a low enough rate that equation (1) is a good approximation to the shock velocity (or at least a reasonable upper limit). In models where shearing motions dominate (Sellwood and Carlberg 1984) there is no systematic difference between the pattern speed and rotation speed. The shock velocities are determined solely by the gravitation of the arms and amount to only a few tens of km s^{-1}. Their dependence on radius is not well determined and is not quantifiable analytically. Finally, models involving stochastic processes (Gerola and Seiden 1974) do not predict coherent global shocks and are not prone to observational tests in the radio. In fact, this type of model is best addressed in terms of the SNR scenario (Paper II). Although it is not the aim of this paper to argue for or against any of these models we proceed with the density wave model for the following reasons.

a) As discussed in Paper II, observations strongly support the density wave picture.

b) It is the simplest of the models and has a well-defined analytical expression for the shock velocity.

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c) It is a good approximation to the Toomre models.

d) Even if not correct in detail, it may shed light on the possibility that rotation is linked to the production of cosmic rays.

We proceed with the classical density wave scenario for the remainder of the discussion. The effect of such a wave and its associated shocks on the interstellar medium of a spiral galaxy is not considered. Consider a homogeneous medium consisting of a mixture of thermal gas and cosmic rays which is permeated by a uniform magnetic field. It is assumed that the three components are in energy equipartition (as observed in our Galaxy). A one-dimensional supersonic shock passing through the medium compresses the medium and enhances the gas and cosmic-ray densities as well as the component of the magnetic field parallel to the shock front. This first-order shock effect results in two important conditions that are conducive to particle acceleration:

i) A concentration (or density) gradient of cosmic rays is established across the shock front. There is therefore a tendency for cosmic rays to diffuse back across the shock front.

ii) Much of the shock energy is thermalized with the result that the turbulence of the downstream gas is enhanced. The turbulent cells and the associated magnetic irregularities act as scattering centers for the cosmic rays. Since the scattering centers move away (downstream) from the shock, there is a tendency both to isotropize and to convect away scattered particles.

These two effects provide necessary starting conditions for the "diffusive shock acceleration," or DSA mechanism (O'C Drury 1983, and references therein). The analytical formulation by Bell (1978*a*, *b*) has been used successfully in Paper II to account for the observed distribution of synchrotron radiation in the spiral galaxy NGC 3310. A brief qualitative description of the mechanism follows.

Because of the concentration gradient of cosmic rays, there is a tendency for the cosmic rays to diffuse back into the low concentration region, upstream of the shock. This tendency is countered by the motion of the scattering centers downstream which carry the cosmic rays away from the shock. If the scattering is isotropic enough, the collective motion of the cosmic rays can be described as a fluid diffusion. Some of the diffusing particles find their way back across the shock and travel upstream with the added energy gained from downstream collisions. As the particles attempt to stream away, they generate instabilities in the form of Alfvén waves. The waves scatter the particles and reduce their bulk motion to roughly the Alfvén velocity. If this velocity is lower than the shock velocity, the shock front catches up to the particles which then end up downstream again. They again diffuse back, and the cycle continues, with a net gain of energy after each cycle. This mechanism works for particles which are already relativistic as well as particles that are merely suprathermal. An equilibrium is reached when cosmic rays are convected away downstream at the same rate as they enter the shock. The balance between diffusion and convection can be represented by a diffusion equation, the solution for which leads to a power-law energy spectrum of accelerated particles (Bell 1978*a*) which, when combined with the equations of Ginzburg and Syrovatski (1965), results in an expression for the synchrotron emissivity of the shocked gas (Bell 1978*a*, *b*; Paper II) that is a function of v_s, the shock velocity.

This mechanism has been applied to SNR with considerable success (Bell, 1978*a*, *b*; Blandford and Ostriker 1978). Given that the mechanism operates in the high-velocity shocks associated with SNR, can it work in low-velocity spiral shocks? In order to answer this question, it is necessary to investigate the conditions required for the mechanism to operate. We begin by listing the relevant conditions and comparing them to the known conditions in the ISM of our Galaxy and in the radio bright galaxy NGC 3310.

III. NECESSARY OPERATING CONDITIONS FOR THE DSA MECHANISM

1. Alfvén waves must not be damped.
2. Energetic particles must stream at less than the shock velocity when upstream.
3. The particles to be accelerated must cross the shock front without being significantly deflected within it.
4. The radius of curvature of the shock must be greater than the scattering length scale.

a) *Damping of Alfvén Waves*

If the Alfvén waves are damped, the DSA mechanism ceases to function, and particles are not accelerated. It is therefore necessary to determine under which conditions this can occur.

Particles of increasing energy generate increasingly weaker Alfvén waves and are less and less scattered. The critical energy above which scattering weakens is expressed by Bell (1978*a*) as

$$\frac{E_{\rm crit}}{\rm GeV} = 0.07\left(\frac{100v_s}{c}\right)^{4/3} n_e^{-1/3} n_{\rm H}^{-2/3} \xi^{2/3} , \tag{2}$$

where v_s is the shock velocity, and the last quantity is the enhancement of the cosmic-ray density above the general galactic background. We use a value of 50 which is appropriate for brighter regions in galaxies such as NGC 3310 (Duric 1986). Since most cosmic rays have energies of less than 1 Gev, we set $E_{\rm crit} = 1$ Gev, which gives

$$v_7^{4/3} 0.05 n_{\rm H}^{-2/3} n_e^{-1/3} > 1 , \tag{3}$$

where $v_7 = 10^7$ cm s^{-1}. For $v_7 = 1$ and $n_e = 0.03$ cm^{-3}, the condition is satisfied if $n_{\rm H} < 0.06$ cm^{-3}, which suggests that a fractional ionization of at least 30% is required. For $n_e = 1$ cm^{-3} the condition is satisfied if $n_{\rm H} < 0.02$ cm^{-3}, indicating that the medium must be highly ionized. Dense neutral media such as hydrogen clouds are excluded because of heavy damping. For example, if $n_{\rm H} = 10^3$ cm^{-3}, $n_e < 10^{-9}$ cm^{-3}. Apart from being unreasonable on physical grounds, this constraint limits the production of Alfvén waves to a negligible level. Hot, low-density gas (as in the coronal phase), where $n_e \approx 10^{-2}$ cm^{-3}, $n_{\rm H} < 0.03$ cm^{-3}, easily satisfies this criterion.

b) *Streaming Velocity*

If the accelerated particles stream faster than the shock velocity, no further acceleration can take place, and the particles are lost upstream. The streaming velocity of particles having momenta p or greater, as formulated by Wentzel (1974), is

$$v_{\rm st} = \frac{1}{3}\gamma v_{\rm A} + \frac{0.19}{\gamma - 3}\left(\frac{T}{10^3}\right)^{0.4} \frac{n_e^{1/2} n_{\rm H}}{N(>p)} , \tag{4}$$

where $N(>p)$ is the number density of cosmic rays having momenta greater than p, γ is the momentum spectral index, and $v_{\rm A}$ is the Alfvén velocity. Using a value of $N(>p)$ typical of the solar neighborhood (Wentzel, 1974) and introducing a scaling factor, χ (ratio of cosmic-ray number density to value in the solar neighborhood), the expression becomes

$$v_{st} = 6.3 \times 10^8 \left(\frac{T}{10^3}\right)^{0.4} \left(\frac{p}{mc}\right)^{1.5} \frac{n_e^{1/2} n_H}{\chi} + 4.2 \times 10^{11} B n_e^{-1/2} \text{ cm s}^{-1} .$$

The required condition is that $v_{st} < v_s$. For $p \gtrsim mc$ ($E \approx 1$ GeV) and $v_s \approx 10^7$ the expression becomes

$$6.3 \times 10^8 \left(\frac{T}{10^3}\right)^{0.4} \frac{n_e^{1/2} n_H}{\chi} + 4.2 \times 10^{11} \frac{B}{n_e^{1/2}} < 10^7 . \quad (5)$$

For neutral clouds ($n_H \approx 10$ cm^{-3}, $n_e \approx 1$ cm^{-3}, $B \approx 3 \times 10^{-5}$ G), $v_{st} \approx 10^9$ cm s^{-1}, which clearly violates the necessary condition, even if $\chi \approx 10$–100. For $n_e \approx 0.03$ cm^{-3}, $n_H \approx 0.01$ cm^{-3}, and $B = 3 \times 10^{-6}$ G, $v_{st} \approx 10^6$ cm s^{-1} and the condition is roughly satisfied. For the regions of higher n_e (as in NGC 3310), $v \approx 10^{6.5}$. For the coronal gas ($n_e \approx 0.01$, $B \approx 10^{-6}$) $v_{st} \approx 10^6$ cm s^{-1}, and it too satisfies the condition.

c) *Crossing the Shock Front*

In order that the DSA mechanism work efficiently, a particle must cross the shock front without being deflected significantly during crossing. The condition for a charged particle is that its gyroradius be greater than the shock thickness.

i) *Neutral Medium*

In a largely neutral medium, the shock energy is transferred to the gas via particle-particle collisions, and the shock thickness is of the order of the mean free path of a neutral hydrogen atom. A charged particle sees the shock front as a discontinuity if its gyroradius is larger than the shock thickness. If this condition is satisfied, the particle's path is unaltered, and it can be injected into the DSA cycle. The mean free path of a hydrogen atom is given by $1/n\sigma^2$, where σ is $\approx 10^{-8}$ cm. The condition can be expressed as

$$r_g > \frac{1}{n\sigma^2} ,$$

which for relativistic protons and electrons is

$$mv_\perp c \bigg/ \sqrt{1 - \frac{v^2}{c^2}}\, eB > \frac{1}{n\sigma^2} , \quad (6)$$

where m is the mass of the particle, e is the electron charge, and $v_\perp$ is the component of the velocity perpendicular to the magnetic field direction. For thermal electrons and protons moving at the shock velocity, the condition is

$$\frac{mv_s c}{eB} > \frac{1}{n\sigma^2} . \quad (7)$$

For relativistic particles, $v \approx c$ and condition 20 is roughly satisfied for both electrons and protons. The thermal particles, however, do not satisfy this condition, since $r_g \approx 10^9$ cm, and the shock thickness is $\sim 10^{16}$ cm. It therefore appears that in a neutral gas only the most energetic (i.e., relativistic) particles are injected into the DSA mechanism.

ii) *Ionized Medium*

In a medium that is largely ionized, collisionless shocks form, whereby energy is transferred by magnetic impulses, not by particle collisions. The shock thickness, in that case, is of the order of a Larmour radius of a thermal proton. The condition for no deflection is

$$\frac{mvc}{eB} > \frac{m_p v_p c}{eB} \rightarrow mv > m_p v_p . \quad (8)$$

For a proton moving at $v \approx 10$ km s^{-1} this becomes

$$mv > 10^{-18} .$$

For protons this is roughly satisfied by default. For electrons of the same energy, the condition is

$$v_e > \left(\frac{m_p}{m_e}\right)^{1/2} v_e' \quad (9)$$

where v_e' is the thermal electron velocity, so that only suprathermal electrons can cross the shock undeflected.

In summary, both electrons and protons can be injected into the DSA mechanism as long as the medium is ionized and the electrons are suprathermal.

iii) *Deflection by Electric Field*

A test particle on the downstream side of the shock sees an electric field potential of the order $m_p v_s^2/2e$. It must have an energy greater than $\frac{1}{2} m_p v_s^2$ in order to be undeflected when crossing the front. The protons have roughly the required energy. The electrons must also have an energy greater than $\frac{1}{2} m_p v_s^2$ (they must be suprathermal). Observations of the Earth's bow shock (Formisano 1974) indicate that roughly equal numbers of suprathermal electrons and protons are injected across the shock front with the energies required to be accelerated by the DSA mechanism.

d) *The Scattering Length and Time Scales*

If the scattering length for the accelerated particles becomes greater than the radius of curvature of the shock front, the efficiency of acceleration declines. The scattering length upstream is given by Bell (1978*a*) as

$$l_{sc} = 5 \times 10^{16} n_e^{1/2} \frac{E^{1.5}}{\text{GeV}} \text{ cm} , \quad (10)$$

which for $E \approx 1$ GeV, $n_e \approx 10 \rightarrow l_{sc} = 1.5 \times 10^{17}$ cm or ~ 0.05 pc. The radius of curvature of a spiral shock is on kpc scales, so that the accelerated particles are always found in the vicinity of the shock and therefore efficiently accelerated. The greater level of turbulence downstream ensures that this condition is also satisfied there. If the gas is clumped the condition can be changed to read

$$l_{sc} < \delta ,$$

where δ is the cloud diameter. Obviously this condition is satisfied for most clouds.

The scattering time is given by

$$\tau_{sc} \approx \frac{l_s}{v} , \quad (11)$$

where v is the particle velocity. For $v \approx c$, the time is ~ 1 yr for 1 Gev cosmic rays. For suprathermal particles, $v \approx 10^{7-8}$, $\tau_{sc} \approx 30$–300 yr. Clearly, the acceleration time is insignificant relative to the lifetimes of the electrons.

In summary, it is apparent that neutral, dense media cannot contain cosmic rays. Although both the intercloud and coronal phases of the medium can confine cosmic rays, the sound speed in the hot phase is comparable to the shock velocity, the gas cannot shock, and the DSA mechanism cannot operate. The only phases of the ISM which satisfy the two conditions outlined above are the warm, partially ionized medium such as the intercloud medium in our Galaxy or a highly ionized denser region such as an H II region (typical of the conditions in the arms of NGC 3310).

IV. SUMMARY

We have shown that given the existence of global shocks, particles can be accelerated to at least the 1 GeV level with maximum efficiency. Even greater energies can be achieved, but with declining efficiency. Protons are easier to accelerate than electrons due to shock deflections, and this may account for the large ratio of protons to electrons in the solar neighborhood. The medium required for acceleration to take place is a largely ionized one with $T \approx 10^4$ K for a dense medium. For less dense media such as the warm intercloud medium in our Galaxy, the required fractional ionization is only of the order of 10%.

The greatest theoretical difficulties lie with the apparent inability of this mechanism to accelerate particles efficiently to energies greater than a few GeV. Although the fraction of cosmic-ray particles with energies greater than a few GeV is very small, it forms an integral part of the energy spectrum of cosmic rays in our galaxy. We suggest that if this is the case in NGC 3310, the high-energy cosmic rays may come from SNR which can accelerate particles to $\sim 10^6$ GeV according to the theory (e.g., Cesarsky 1984). No break in the energy spectrum would result if the SNR accelerate particles already accelerated by the global shocks. The acceleration of particles to energies greater than 10^6 GeV still remains a mystery (see, however, the suggestive articles by Wolfendale 1983 and Henbest 1983).

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