COSMIC RAY SECONDARY NUCLEI AND THE STRUCTURE OF THE GALAXY

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ABSTRACT. We explore the consequences of diffusive acceleration of cosmic rays in supernova shocks propagating through an inhomogeneous interstellar medium. The acceleration takes place in the hot, tenuous, intercloud gas, whilst nuclear collisions, leading to the production of cosmic ray secondaries, predominantly occur in those regions where the supernova shocks collide with interstellar clouds. We use a simple model to calculate the interaction of a (cosmic ray + gas) shock with a cloud, and thus determine the gross topology. Extending this to the whole system, using mean cloud sizes and space densities, allows us to calculate the secondary/primary cosmic ray abundance ratios for light and heavy nuclei.

1. INTRODUCTION. The antiproton/proton abundance ratio in the cosmic rays of a few GeV/n [1] is about 4 times higher than expected on the basis of a model describing the galaxy as a simple leaky box (SLB). The $^3He/^4He$ ratio, also at a few GeV/n, was found to be enhanced by a factor of about 2, using the SLB model [2]. The idea of invoking "thick-target" sources to explain the antiproton observations has recently been introduced [3,4]. In this model a fraction of the cosmic rays sources is assumed to be located in massive, dense, interstellar clouds (i.e. buried supernovae). The clouds essentially absorb the locally produced heavy primaries and secondaries, but allow a significant fraction of light primaries and secondaries to escape. This source thus enhances the secondary/primary ratios for the light particles, provided the mean matter path length in the source region is sufficiently large (of the order $40 g/cm^2$). The remainder of the sources is located in a low density medium, producing cosmic rays that traverse about $6 g/cm^2$ of matter before being lost from the galaxy. This yields the observed secondary/primary ratios of the heavier nuclei. Difficulties with this model arise from galactic gamma-ray observations which imply that embedded sources can not be effective producers of energetic (GeV) cosmic rays [5]. A second problem is the ionization rate inferred for the massive clouds. For $\dot{E}$ ergs/sec injected into massive clouds, of which a fraction η goes into ionizing the gas, and assuming that 10 eV is required for ionization, we compute an ionization rate

$$\xi = 5 \times 10^{-15} \frac{\dot{E}}{\dot{E}_s} \eta \qquad (\mathrm{sec}^{-1})$$

This assumes a total cloud mass of $10^9 M_\odot$. $\dot{E}_s$ is the standard cosmic ray energy input rate computed from confinement time measurements ($=10^{41}$ ergs/sec). Thus for an efficiency of ~ 0.2, we still obtain mean ionization rates which exceed the typical observed levels by about two orders of magnitude.

Nevertheless, the idea of "thick-target" sources is very appealing to explain the cosmic ray observations because of its basic simplicity.

We therefore explore whether supernova shocks propagating through an inhomogeneous interstellar medium, interacting with clouds locally and advecting previously accelerated particles into these "absorbers", exhibit some "thick-target" properties. In principle this should be so, the question is of course, "at what price do we obtain quantitative agreement?"

2. THE MODEL. We assume that cosmic rays are accelerated in supernova shocks, when these propagate through the hot ionized intercloud medium [6]. We then calculate in a simplified model how the interaction with an interstellar cloud proceeds. The physical processes considered were:
(1) As long as the cosmic ray energy density exceeds that of the gas, magnetohydrodynamic waves are excited by the streaming instability [7].
(2) Through wave-particle interactions the cosmic ray "gas" can then couple onto the thermal gas and modify its flow.
(3) In the ionized medium wave damping is slow so that this coupling is very close. We then have a mixture of a thermal gas and a relativistic, essentially massless, cosmic ray gas acting as a single fluid.
(4) In the neutral clouds, wave damping by ion-neutral friction is very efficient [8]. As a result, the cosmic rays do not interact with the neutral cloud gas and the two are completely uncoupled, at least parallel to the magnetic field $\underline{B}$.
(5) When the cosmic ray energy density equals that of the gas, wave production by the streaming instability ceases and cosmic rays are no longer tied closely to the interstellar medium. A hydrodynamic treatment then becomes inappropriate; cosmic ray transport is diffusive.
(6) Cosmic rays are, however, absorbed in the cloud by nuclear collisions and ionization losses. Through these processes both energy and momentum are taken out of the cosmic ray gas and deposited inside the cloud.
(7) The cosmic ray energy density is dominated by the most abundant species: the protons. Hence, the dynamics of the system is determined by their fate. Cosmic ray secondaries as well as the heavier primaries have to be discussed within the physical framework set up by this dominant component.

This gives rise to the following picture (Fig. 1):

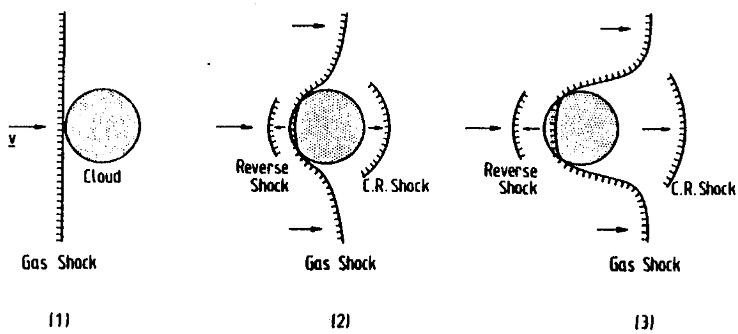

Fig. 1: Illustration of the interaction of a supernova shock, including accelerated cosmic rays, with an interstellar cloud.

The supernova shock with its accelerated cosmic ray component hits the interstellar cloud (1). There is magnetic connection across the cloud, permitting the cosmic rays to enter at essentially the speed of light and to emerge on the other side. The cloud, therefore, acts like a filter, letting cosmic rays through, but not the gas. On the other side, the cosmic rays once again couple onto the tenuous, ionized intercloud gas and produce a cosmic ray pressure driven shock wave (CR) which displaces this gas. The hydrodynamic shock inside the cloud is very slow, and the gas shock begins to envelope the obstacle. There may also be a reverse shock (RS) propagating away from the cloud back into the supernova remnant (2), and cloud evaporation at the contact surface [9]. As time progresses, the gas shock begins to catch up with the (somewhat weaker) cosmic ray shock (3). There may be complicated contact surfaces and reflected shocks, etc. which only a numerical calculation could unravel. For our purposes we shall ignore this and represent the complicated sequence of events with a simple one-dimensional model. By ignoring cloud "crunching" and assuming that evaporation will not be overly significant, we can regard the cloud column density as constant.

3. RESULTS. Figure 2 shows the results of our calculations. We explored a whole range of parameters for the cloud column densities, filling factors, densities, etc. For a full discussion see [10]. Fig. 2 represents the best fit we were able to obtain. As can be seen, the "anomalous" antiprotons and ^{3}He can be explained quite naturally within our theory.

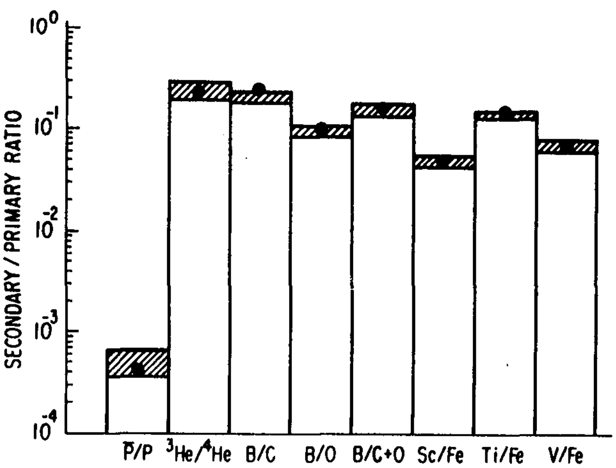

Fig. 2: Comparison between observed (hatched bars which show the measurement uncertainties) and calculated (solid circles) cosmic ray secondary/primary ratios. The model parameters are given in the text.

The structure of the interstellar medium, derived from the fit to the observed secondary/primary ratios, is summarized in Tables I and II.

Table I: Structure of the interstellar medium

Intercloud medium	
density	10^{-2} cm^{-3}
temperature*	4.3×10^5 K
filling factor	0.92
pressure*	0.8 eV/cm^3

Table II: Structure of the interstellar medium Clouds (average properties)	
gas density	$120 cm^{-3}$
column density	$1.1 \times 10^{21} cm^{-2}$
size	3 pc
temperature*	80 K
mass	$94 M_\odot$
spatial density	$2.9 \times 10^{-3} pc^{-3}$
mean separation (line of sight)	40 pc
filling factor	0.08
total mass in galaxy	$1.9 \times 10^{10} M_\odot$

*Not derived from the cosmic ray data, these are input values.

It should be stressed that the measurements pertain to the volume sampled by the cosmic rays, i.e. a region within about 1 kpc of the solar system. Extrapolation to the galaxy as a whole may therefore not be valid. The galactic gamma ray luminosity calculated from this model is 3×10^{38} ergs/sec, in good agreement with measurements [11]. The derived quantities of Tables I and II agree surprisingly well with the interstellar medium structure derived by McKee and Ostriker [12].

No attempt has been made to calculate the secondary spectra, although it is easy to show that the total matter path length traversed by very high energy particles should become progressively smaller, in qualitative agreement with observations.

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