Propagation and Acceleration of High-Energy Cosmic Rays

Michael Hillas (University of Leeds)

INTRODUCTION

This **introduction** contains brief remarks on the scope of the lectures, with some comments on the selective nature and incompleteness of the treatment.

It is followed by the material presented in the lectures –
(A) Summary notes handed to the students before the lectures, and
(B) the viewgraphs shown in the 3 lectures, which were (1) on background material and propagation at energies below the knee, (2) Acceleration, concentrating on an introduction to diffusive shock acceleration, and (3) extragalactic cosmic rays.

Finally, a ``**Postscript**'' adds some notes on matter that was raised in questions, revealing areas that were evidently not well explained in the talks.

Lecture 2, on the acceleration of (mainly Galactic) cosmic rays, concentrated almost entirely on one mechanism – diffusive shock acceleration – as this is by far the best developed and most promising model of acceleration, much more amenable to quantitative development and predictions than is often the case in cosmic ray physics. However, the lecture attempted to give a general understanding of the model, and the features which make it attractive, by using a simplified treatment. The result is an optimistic account of the model, including a development which may indeed explain some detailed features of the cosmic-ray ``knee'', to show that it is of great interest in the domain of high-energy cosmic rays. However, there are some problems with this over-simplified treatment, that are at the heart of current observational and theoretical work on supernova remnants. The main problems and complications will be mentioned here to put the lecture in context.

In the simple early consideration of diffusive shock acceleration, known as the ``test particle approximation'', it was not realised how very efficient the process was likely to be in generating cosmic rays, and the pressure of the ``cosmic-ray gas'' itself was considered negligible. In this case, and if the pressure of the external gas is negligible (in effect, the speed of the supernova shock wave is very large compared with the speed of pressure waves in the external gas), simple conservation laws show that the gas density should jump by a factor 4 on passing through the shock, and this factor determines the energy spectrum of relativistic particles accumulated inside the SNR to have a spectral exponent $\gamma = 2.0$. It has also been long believed that cosmic rays are trapped near the Galactic plane for a time proportional to $E^{-0.6}$ before escaping altogether, so a spectral exponent $\gamma = 2.7$ could result for the cosmic rays around us if the source released particles with a spectral exponent 2.1, very close to what is expected for the particles accumulating in the SNR according to the simple model. This was regarded as a great achievement. Because it now appears that the cosmic rays are trapped for a time varying as $E^{-0.33}$, this point was somewhat emphasised in lecture 1, as it implies that the sources must be releasing particles with a spectral exponent about 2.36 rather than 2.1. This in itself indicates that we require a slight change to the model, in order to achieve this, but this may not be a major difficulty as the particles inside the SNR have a steeper spectrum when the SNR slows down, and so we need to know just when most of the cosmic-ray particles inside are released into the Galaxy.

However, if cosmic rays are generated so efficiently that their energy density is similar to that of the ordinary Maxwellian part of the hot gas, as seems likely to be the case, the gas pressure is changed – as relativistic particles have a pressure equal to 1/3 of their kinetic energy density, whereas non-relativistic atoms in a gas exert a pressure nkT in a common

notation, which is 2/3 of their kinetic energy density, 3/2 kT per atom. (Electrons can, strangely, be neglected, as they gain the same speed as atoms on passing the shock, rather than the same energy.) So the factor 4 density jump is altered, and, moreover, the ``cosmic rays'' diffusing just ahead of the shock will significantly pre-compress the gas being swept up, increasing the compression. It is hence predicted, that in the upper part of the energy range, the spectral exponent of accelerated particles accumulating in the SNR will be more like 1.75 than 2.0 ! The simple compression factor 4 is not a universal expectation any more. There is no sign of such a ``hardening'' of the spectrum of cosmic rays in the Galaxy, nor, yet, in SNRs (TeV gamma-rays).
However, if very efficient production of cosmic rays does *not* occur, Bell's recent model for producing the high magnetic field and, as a result, the knee at 3 PeV, would not work. (Also we could not then account for the energy density of cosmic rays in the Galaxy.)

Another fact not yet understood is the low level of the TeV gamma-ray flux from some SNRs, indicating much less efficient production. One possibility being explored is that efficient production does occur, but only over a fraction of the SNR's shock surface.

So, there are aspects of the model not yet fully understood, and it was decided to present the basic outline of the model in the lectures, and not dwell on these problem areas that present an important task for theorists.