The Extra-Galactic Contribution to the Primary Cosmic-Ray Flux

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The extra-galactic contribution to the primary cosmic-ray flux

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In previous studies it has been shown that a good case can be made for supposing that a large fraction of the primary cosmic rays is of extra-galactic origin. These ideas are reviewed here, and the most recent observations and theoretical suggestions bearing on the problem are described.

1. Introduction

There have been many proposals concerning the possible sources of cosmic rays. In modern times several different ideas have been widely discussed. For a number of years the idea that cosmic rays largely originated in the Sun was canvassed by Teller, Alfvén and others. In the early 1950s Fermi proposed that, while the cosmic rays might arise in different kinds of galactic sources, a stochastic acceleration mechanism – the Fermi mechanism – working in the interstellar medium was the primary energy-generating mechanism. By now both of these theories appear unlikely. A solar origin for the bulk of the cosmic rays is excluded both on energetic grounds and also because the chemical composition of the sources is clearly different from that of the Sun. It is also agreed that the Fermi acceleration process working in the interstellar medium is not efficient enough to maintain the observed flux of cosmic rays.

It has therefore been natural to move toward theories in which it is supposed that the cosmic rays come from highly energetic sources, many of which have been discovered in the last twenty years. In particular, the discovery of strong non-thermal radio sources gave direct evidence that in and after stellar and galactic explosions very large fluxes of relativistic particles are generated. In all cases, the existence of synchrotron radiation only establishes directly that electrons are present. Proof that protons or heavier nuclei are also present can only come through indirect arguments, or, as has been described at this meeting, by the detection of γ-rays which have come from π^0 decay following collisions between relativistic protons and the ambient gas in the source.

The synchrotron sources fall into two major classes:

(*a*) The sources in our own Galaxy which are thought to be supernova remnants.

(*b*) The extra-galactic sources, which, while they have a wide range of activity levels, all appear to originate in some types of galactic explosions.

It is natural to suppose that supernova remnants can give rise to a galactic cosmic-ray flux, provided that the cosmic rays can diffuse significant distances. On the other hand the particles from the much more powerful extra-galactic sources diffuse through the intergalactic medium and give rise to an extra-galactic cosmic-ray flux which can, in principle, fill the whole Universe.

Which of these two components is likely to dominate in the cosmic-ray flux, which is detected at the top of the Earth's atmosphere?

In their book (Ginzburg & Syrovatskii 1964) and in later reviews Ginzburg & Syrovatskii

(1967, 1971; Ginzburg 1969, 1970) devoted most attention to the development of a comprehensive galactic theory, while heavily criticizing the universal extra-galactic theory on energetic and on other grounds. The extra-galactic theory was originally developed in 1962 (Burbidge 1962) and further discussed by Burbidge & Hoyle (1964) and Burbidge & Burbidge (1965) and by Setti & Woltjer (1971) and Shklovskii (1971). The most extensive development of this theory is due to Brecher & Burbidge (1972) (see also Burbidge & Brecher 1971) and a number of the points to be discussed below were analysed fully by Brecher & Burbidge.

For each class of source it is necessary to show that it has the cosmic-ray composition (extrapolated to the origin) and that both the nucleons and electrons are accelerated to give the spectral form seen in the primary spectrum. While different elements may be accelerated in different sources, a good case has been made for arguing that much of the cosmic-ray composition is that synthesized in explosive nucleosynthesis (Arnett & Schramm 1973). While this idea fits naturally into a scheme involving galactic supernovae as the primary cosmic-ray sources, such explosive nucleosynthesis can equally well take place in explosive events in the nuclei of galaxies. As far as the energy spectrum is concerned, in almost all theories it is claimed that a spectral shape of roughly the correct form can be obtained (Burbidge & Hoyle 1964; Colgate & Johnson 1960; Gunn & Ostriker 1969). Of great importance is the experimental shape of the primary spectrum, throughout the whole range 10^{10}–10^{20} eV (cf. Wolfendale 1974).

The discovery of the pulsars, and the general acceptance of the view that they are supernova remnants, has given further stimulus to the idea that supernovae are the primary sources of cosmic rays (cf. Gold 1974). Again, the general idea can well be taken over in the framework of the extra-galactic theory since it has been argued that galactic explosions are associated with clusters of pulsars or with giant pulsars (spinars). The difficulty is that we really have no clear understanding of the way in which pulsars do accelerate particles, nor do we know what the ratio of nucleons to electrons is likely to be in such processes. Also, it does not appear possible to generate and accelerate heavy nuclei in the vicinity of pulsars.

2. The extra-galactic component

We now investigate whether we can satisfy the main requirement of an extra-galactic theory – namely to show that distant sources can fill up very large volumes of space with relativistic particles, so that it can reasonably be argued that our own Galaxy is bathed in cosmic rays. We discuss successively the energetics of the sources and the propagation of the particles. For full details the reader is referred to Brecher & Burbidge (1972).

Energetic considerations

To fill the Universe with cosmic rays at an energy density of 10^{-19} J cm^{-3} we require tha each galaxy assumed to have a mass of 10^{11} $M_{\odot}$ inject about 10^{56} J of relativistic particles in 10^{10} years (a); alternatively it can be argued that since the mean density of visible mass in the universe is about 10^{-31} g cm^{-3}, an energy density of 10^{-17} J cm^{-3}, about 1 % of the mass–energy density, should be in the form of relativistic particles. This is the requirement for the most energetic cosmic-ray model – a truly universal cosmic-ray flux.

Can synchrotron sources reasonably be expected to pump this many particles into intergalactic space?

For any individual source it is difficult to estimate the total activity for the following reasons.

If we can measure the flux of radiation from a source, its spectral form, and the size of the region from which it comes, we can make calculations of the energy content of the electrons in the source on the assumption that they are radiating non-coherent synchrotron radiation and that there is approximate equipartition between electron energy and magnetic-field energy ($E_p = \frac{4}{3}E_m$). These calculations have been made for a number of nuclei (Demoulin & Burbidge 1968; Burbidge & Stein 1970). In this model it is always found that the total energy available depends on the size of the source ($E \propto R^{\frac{9}{7}}$) and the characteristic timescale $\tau \propto R^{\frac{9}{7}}$, while the characteristic timescale for radiation is the light travel time across the source, i.e. $t \approx R/c$. This means that we cannot obtain any certain estimate of the total flux of relativistic particles generated except by making some assumptions about how long the activity lasts.

When strong radio galaxies were first discovered, it was realized that they were rare in comparison with normal galaxies. It was argued that, if every galaxy has an equal *a priori* probability of generating a strong radio source in its lifetime (assumed to be about 10^{10} a) of unity, then the average period of violent activity $\approx 10^{10}f$, where f is the fraction of galaxies which are strong radio galaxies. The fraction f was originally estimated to be 10^{-3} to 10^{-4} (Burbidge 1962). The total flux of relativistic particles generated in a Hubble time is then equal to the total particle energy estimated to be present in a typical galaxy multiplied by the total number of galaxies. Since the equipartition calculations suggest that in the strong radio sources the total energy available lies in the range 10^{52}–10^{54} J, depending on the size of the source and the assumptions made about the proton–electron ratio, the total cosmic-ray energy density generated by such sources would on these assumptions be only about 10^{-23}–10^{-21} J cm^{-3}, a value very much smaller than the energy density of local cosmic rays $\approx 10^{-19}$ J cm^{-3}. It was this chain of argument which originally led Ginzburg & Syrovatskii (1964) to discount, on energetic grounds, the extra-galactic cosmic-ray hypothesis. However, it had been pointed out earlier by Burbidge (1962) that the concept of energy equipartition was the most *conservative* assumption that could be made to explain the power radiated by a synchrotron source (Burbidge 1956) and that it has no basis in a physical model. If the equipartition is violated in the sense that $E_p \gg E_m$ so that the total particle energy emitted over the lifetime of a galaxy is as large as 10^{56} J; and if the active period lasts for about $fH_0^{-1} \approx 10^6$ a, then the universal energy density could easily amount to about 10^{-19} J cm^{-3}. Schmidt (1966), pointing out that a significant fraction of the optically identified strong radio galaxies are D systems, estimated that since about 10% of the D systems are strong radio sources, if it is this limited class of galaxy that is able to generate a radio source, the harmonic mean life of such a source is $10^{10}f$ years, where now $f \approx 0.1$. If now these are the sources largely responsible for extra-galactic cosmic rays, the total number of sources is much less, and consequently the energy per source required to give a universal energy density of 10^{-19} J cm^{-3} amounts to about 10^{58} J, a value thought to be excessively large. So the universal cosmic-ray hypothesis has been discredited on this ground also. However, there are a number of ambiguities in this argument. While a considerable number of optically identified radio galaxies are D systems – bright ellipticals with extended halos – many are N systems, which are akin to quasi stellar objects. Whatever the underlying object that has given rise to the radio and optical emission in these objects, it has completely changed their optical appearance so that no estimate of their importance can be made by comparing the numbers of radio emitting N systems with normal systems. Something similar may be true of D systems. While D systems which are not radio sources are present in considerable numbers, it is not out of the question that the halo structure of D systems is due to activity in their nuclei so that the optical appearance of these galaxies is not completely due to starlight. If this is the case, the frequency arguments are meaningless. Taken at their face value Schmidt's results lead to lifetimes in an active radio phase of about 10^9 a for D systems. In this time the total radio energy output may amount to about 10^{54} J. This is equal to or greater than the total energy content estimated from equipartition arguments, and yet much of this latter energy probably is in relativistic protons and is therefore not available for synchrotron emission. This by itself suggests that the total energy generated in particles is much greater than the equipartition value; and *if* these galaxies are active for such a long period, then continuous high-level generation of particles is indicated.

In recent years it has been found that many radio sources contain very small high surface-brightness components whose angular sizes are 10^{-3}–10^{-4}″. At the same time the radio spectra of these components show a turnover which is almost certainly synchrotron self-absorption. From the data it is possible to calculate the strength of the magnetic field and it is then normally found that the particle energy is many orders of magnitude greater than the magnetic energy. This then may be a pointer towards the conditions in the sources generally.

What of other sources of synchrotron radiation? The only other distinctive class of object which is known to be emitting non-thermal optical or infrared radiation is the class of Seyfert nuclei. The classical argument is that, since they comprise about 1% of the bright galaxies, the Seyfert phase lasts a total time of about 10^8 years. The estimate of the frequency of Seyfert nuclei is based on a limited sample of nearby galaxies, and while by now many fainter Seyfert nuclei have been detected, it has not yet been possible to estimate their frequency, as compared with normal galaxies. It has been known for some time that there is a non-thermal optical synchrotron component in these nuclei, and the physical conditions in them were investigated by Demoulin & Burbidge (1968). Recent investigations have shown that some of these are powerful emitters of infrared radiation at power levels of 10^{38}–10^{39} J s^{-1}. Emitting an infrared flux at these levels for about 10^8 a, these galaxies in their lifetimes radiate a total flux of 3×10^{53}–3×10^{54} J. It seems most likely that the flux is non-thermal emission arising from relativistic electrons which radiate either through the synchrotron process or the Compton effect, and that the energy ultimately comes from gravitational sources. Thus, this integral is a measure of the total generation of relativistic electrons over the life of a galaxy. Clearly, if we could determine the production ratio of relativistic nucleons to electrons in the acceleration process in the galactic nuclei, we could estimate the total flux of cosmic rays that can be generated by a galaxy. With the numbers given above, to obtain the magic number of 10^{56} J per galaxy, we need $E_n/E_e \approx 30$–300.

This method of estimating the total flux does not take into account the various sources of particles which have so far not been identified as point sources. We have no way of taking such sources into account except to consider the microwave background radiation and suppose that some fraction of it is generated by discrete sources. When this is done, it can be shown on the basis of quite conservative assumptions (Burbidge & Brecher 1971; Setti & Woltjer 1971) that provided $E_n/E_e \gtrsim 100$, with only a small fraction of the microwaves coming from discrete sources, it is quite easily concluded that a dominant extra-galactic cosmic-ray flux can be generated.

While I shall not elaborate on this point here, care must be taken in applying this argument, since the microwave background photons will attenuate very high energy cosmic rays, and the attenuation is directly proportional to the energy density of the radiation.

The problems of propagation

Given that enough cosmic rays could be generated to fill the Universe to a fairly high energy density, can they propagate over intergalactic or intracluster distances?

The electron component suffers energy losses by synchrotron radiation and by Compton scattering. It is well known that effects of Compton scattering on the microwave background are strong enough so that the bulk of the primary electrons cannot propagate from one Galaxy to another (cf. Brecher & Burbidge 1972). Thus, the primary electrons detected in the cosmic rays must be of galactic origin, and not all cosmic rays are extra-galactic.

As has already been mentioned, at very high energy the nucleonic flux will also be attenuated by interactions with photons. However, for the bulk of the flux, close to the mean energy of about 10^{10} eV/nucleon, the only energy dissipating process is collisions with ambient gas atoms. Therefore, it has frequently been stressed that if the intergalactic matter density is high enough, a universal cosmic-ray flux with high energy density ($\approx 10^{-19}$ J cm^{-3}) could not be present, otherwise the flux of γ-rays from π° decay would be greater than the flux observed.

The point that must be stressed here is that there is no direct evidence for the presence of intergalactic gas at the comparatively high density required to close the Universe, $\rho_c = 4.7 \times 10^{-30}$ g cm^{-3} obtained when H_0 (Hubble constant) = 50 km s^{-1} Mpc^{-1} and q_0 (the deceleration parameter) = 0.5. Strenuous attempts have been made to look for diffuse gas through absorption measurements if it is cool, and by detection of bremsstrahlung X-rays if it is very hot. Reviews of the situation have been given by Burbidge (1971), Field (1972) and Burbidge (1973). Attempts to detect absorption in the 21 cm line or in Lyα have led to null results. A background flux of X-rays of extra-galactic origin has been detected, and there has been much discussion about its origin. It might be thermal bremsstrahlung or Compton radiation. If it is Compton radiation, there is no evidence for any hot gas. It appears likely that the background is the integral of the flux from a large number of discrete sources. If this is the case, then even if the radiation is thermal bremsstrahlung, this comes from gas in sources which may be Seyfert galaxies, other types of galaxies, quasi-stellar objects, or clusters of galaxies.

There is therefore no evidence for general intergalactic gas which would interact with a universal cosmic-ray flux. Thus, if cosmic rays did pervade the whole Universe, they would not suffer significant energy losses in the space between the clusters of galaxies.

At the same time it is unlikely that cosmic rays can travel intracluster distances in the time available to them. Since it is well known that galaxies show very strong clustering tendencies, the cosmic rays will be generated largely in clusters and must propagate through the cluster medium. It is clear that some gas and magnetic field is present in these regions and our studies (Burbidge 1962; Brecher & Burbidge 1972, §IV) suggest that the cosmic rays will only slowly diffuse through a cluster or supercluster gradually filling it with relativistic particles. While the parameters are very uncertain, it appears that it can take times of order 10^9–10^{10} a for particles to diffuse out of the clusters or superclusters.

This leads us to the important conclusion that extra-galactic cosmic rays are not likely to fill the whole Universe. Instead, they will gradually fill up clusters and superclusters which only occupy about 1 % of the total volume. Thus the energy requirements for a realistic extra-galactic theory, if clusters are filled to the level of the local cosmic-ray density, only amounts to about 10^{-19} J cm^{-3} in 1 % of the total volume, or a mean energy density of about 10^{-21} J cm^{-3}.

Finally, there is direct evidence that active galaxies in clusters generate large fluxes of relativistic particles which have in some way managed to fill very large volumes. The extended radio sources give direct evidence for the existence of relativistic electrons and, remarkably, the mean radio spectral index for strong sources is $\alpha \simeq -0.75$, which means that the primary electron spectrum is of the form $N(E) \propto E^{-2.5}$, a value which is remarkably close to that of the primary cosmic-ray proton spectrum where $N(E) \propto E^{-2.75}$ (Ryan, Ormes & Balasubrahmanyan 1972). It is well known that while the average size of an extended radio source is only of order 100 kpc, some sources have dimensions closer to 10^6 pc, and one of these is the nearest radio galaxy NGC 5128 (Centaurus A). In addition to this, active galaxies in the Coma cluster, and in the Perseus cluster, have apparently pervaded very large volumes with relativistic particles. It should be emphasized that we still have very little idea of how the particles propagate from the galactic nuclei (for a discussion of this problem see DeYoung & Burbidge 1973). However, for this discussion it is enough to point out that we have direct observational evidence from radio astronomy that electrons which are much more vulnerable than protons are found millions of parsecs from the site of the outburst.

As was mentioned earlier, the existence of X-ray sources in clusters of galaxies also may indicate that relativistic particles pervade the cluster. This is the case if the X-ray sources are due to Compton scattering, but not, of course, if they are thermal radiation from a hot gas.

TABLE 1. MAIN CONFINEMENT REGIONS FOR DIFFERENT COMPONENTS OF THE COSMIC-RAY FLUX

	Galaxy	Virgo super-cluster	Universe
electrons ($e^{\pm}$):			
$E_e \geqslant \frac{1}{2}$ GeV	1†	excluded	excluded
$E_e \leqslant \frac{1}{2}$ GeV	1	2	excluded
protons:			
$10^9 \leqslant E_p \leqslant 10^{16}$ eV	2	1	excluded
$10^{16} \leqslant E_p \leqslant 10^{19}$ eV	3	2	1
$E_p \geqslant 5 \times 10^{19}$	2	1	excluded
light nuclei, Li, Be, B	1	2	excluded
^{10}Be	1	excluded	excluded
heavy nuclei ($6 \geqslant Z \geqslant 92$)	2	1	excluded
superheavy nuclei ($Z > 92$)	1	excluded	excluded

† 1, primary importance; 2, secondary importance; 3, lesser importance.

3. CONCLUSIONS

I have summarized some of the evidence which indicates that a large part of the primary cosmic-ray flux may be of extra-galactic origin. As is the case for the galactic origin theory, the evidence is largely circumstantial. Direct evidence that a large energy density of cosmic rays is present outside our own Galaxy is not yet available. A test of this hypothesis, involving the detection of γ-rays from the Magellanic Clouds, which could be used in the negative sense only, has been proposed by Ginzburg (1972).

If many cosmic rays coming into the Solar System are extra-galactic, they most likely come from active galaxies in the central region of the Virgo cluster, from Centaurus A, or from M82. Not all of the cosmic-ray components can have an extra-galactic origin, and in particular the primary electrons and the very heavy nuclei must be largely of galactic origin. I reproduce in table 1 the table from the paper of Brecher & Burbidge (1972) in which we attempted to give a detailed breakdown of possible regions of origin. For the major energetic component, the primary protons, the experimentalists at this meeting have suggested, among other possibilities, that the isotropy and the primary spectrum can both be interpreted in terms of an extra-galactic origin (Elliott 1974; Wolfendale 1974).

There is one final point. It has been suggested by Parker and others that, even if our Galaxy is bathed in an external flux of cosmic rays, it may be very difficult for them to enter the Galaxy and then leave again unless there is a completely open magnetic field geometry. This indeed may be the case. At the same time it appears to me that it would be a highly unrealistic picture to argue that the Galaxy could really be sealed indefinitely against an inward flow of particles. If they are there, they will surely eventually get in and the field conditions and the dynamical conditions will be modified so that a steady flow through, with some trapping in the galactic disk, will occur.

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