CONCLUDING REMARKS

Giancarlo Setti
Istituto di Radioastronomia CNR
University of Bologna, Italy

It is, of course, difficult to attempt to reach any general conclusion at the end of this Symposium where we have dealt with the physics of cosmic rays in so many different astrophysical conditions. As Prof. Ginzburg mentioned in his introductory talk, a much more appropriate title of the symposium would have been "Cosmic Rays Astrophysics". Alternatively, one may propose "Origins of Cosmic Rays" adding an s to the original title. In this respect the most spectacular sites in the universe, whereby large amounts of energy are released in the form of relativistic particles, are to be found in active nuclei of galaxies, such as radiogalaxies, Seyferts' nuclei, etc. We still don't know what the ultimate source of energy is in these active nuclei, nor do we know how particles are so effectively accelerated, both in these compact objects or in the outer regions, such as the radio lobes of extended radio sources. However, whatever the detailed acceleration mechanisms may be, and whatever the precise nature of the ultimate energy source is, at least in this case it is clear where the "origin" of cosmic rays must be located. So, it is perhaps better to focus our attention on some definite subject, such as the problem of the origin of the "classical" cosmic rays, which, it seems to me, is still a largely unsolved problem. Here, I am listing a number of relevant topics, which, I feel, deserve further consideration and which may form the basis for the general discussion to follow. Since the time at our disposal is rather short, I will go very quickly in illustrating them.

The first point to be mentioned is the confinement region of cosmic rays in the Galaxy. During the meeting there was some discussion about the existence of a halo, or a "thick disk", as the trapping region of cosmic ray particles. It must be recalled at the start that in the framework of the galactic theory for the origin of cosmic rays the question of the existence of the halo has nothing to do with the energy requirements. The overall energy balance ultimately depends on the total amount of gas present in the Galaxy, which is mainly confined to the galactic disk. If I remember correctly, originally one of the main supporters of the existence of a quasi-spherical halo was the high degree of isotropy of the cosmic rays: a large volume surrounding the Galaxy in which the relativistic particles would be scattered many times

G. Setti, G. Spada, and A. W. Wolfendale (eds.), Origin of Cosmic Rays, 399–403.

https://doi.org/10.1017/S0074180900074969 Published online by Cambridge University Press

back and forth. Now we know that there are several mechanisms by which particle trajectories can be effectively isotropized even within relatively small volumes in the galactic disk. As has been shown by Dr. Sancisi, radio observations of external galaxies have led to the discovery of a few spiral galaxies which possess more or less "flat" haloes. Although these findings are of great importance, there are a number of questions which are left unanswered. In particular, on the morphological side, we would like to know how this property correlates with the galaxy type and, even more important, how it correlates with the total power emitted at radio wavelengths. As far as I can judge, the existence of an external halo in M31, which is similar to our galaxy in its radio output, is still very much controversial.
In our own galaxy the distribution of relativistic electrons, which is inferred from the radio observations, appears to be thicker than the interstellar gas layer. However, a closer inspection of the galactic non-thermal radio emission reveals a rather complex distribution characterized by a number of features sticking out of the galactic plane, while in between these features, very little emission, if any, is sometimes recorded. Although the interpretation of the data is not straightforward, it is clear that the observations do not provide direct evidence of the existence of a large trapping volume in which the cosmic rays can be effectively confined for the required length of time. Moreover, to keep the cosmic rays down, the full weight of the interstellar gas is needed via the coupling provided by a rather weak magnetic field, and this is certainly difficult to achieve at great distances from the galactic plane. An alternative picture is the one in which cosmic rays are produced and remain confined essentially within the gaseous galactic disk for a few tens of million years and then propagate outward forming some sort of a galactic wind. Unfortunately, the position of the Sun close to the plane of symmetry of the Galaxy is not suitable to detect the effects of a gradual flux of cosmic rays out of the Galaxy. The more or less flat radio haloes one observes in some spiral galaxies may be just the result of this outward diffusion, or convection, of relativistic particles. It is to be hoped that future observations, and, in particular, high-resolution, high-sensitivity radio observations at different wavelengths of a suitable sample of spiral galaxies, will ultimately permit a better understanding of how relativistic particles and fields get out of the parent galaxies and of the physical parameters which control their propagation. This, in the end, is the relevant physical problem one wishes to understand, quite independent of the implications it may have on the economy of the cosmic rays in our galaxy.

The second important point which was discussed in this conference was the question of the uniqueness of the sources of cosmic rays. Various arguments based on the isotopic composition and on the electron component seems to indicate that perhaps supernovae are not "*the sources*" of galactic cosmic rays, or at least that they may not be the dominant contributors. A further argument which points toward the same conclusion is provided by the ratio between the energy densities in the proton and in the electron components. This ratio is $\gtrsim$ 100 in the cosmic rays. We may now ask, "What is this ratio in the SN remnants?" In the case of the Crab Nebula it is well known that the ratio between protons and electrons energy densities cannot be very much different from unity. Let me quickly summarize the main arguments here. The first argument relates to the acceleration of particles presently taking place in this object and presumably due to the activity of the pulsar: If one takes canonical parameters for the neutron star and the observed slowing down of the pulsar period, one finds that about 40% of the rotational energy loss goes into the acceleration of the relativistic electrons to compensate for the radiation and adiabatic expansion losses. The second argument relates to the past history of the Nebula: One can show that the total kinetic energy involved in the acceleration of the shell to its present expansion velocity, presumably due to the pressure exerted by the relativistic gas, is about twice the total energy of the reservoir of relativistic electrons present in the Nebula. All together these two arguments show that the acceleration processes taking place inside the Nebula, and near the pulsar, are such as to channel about the same amount of energy in protons and electrons.

By inference one can assume that a similar situation exists for the other SN remnants, although the situation there is admittedly much less clear.

It may be pointed out here that the total kinetic energy in the shell amounts to $\gtrsim 2 \times 10^{49}$ erg, while at least 10^{50} erg must be supplied in cosmic rays by a typical supernova to satisfy the energy requirements. Of course, the Crab Nebula may not be representative of a typical SN remnant. It is, however, rather unsatisfactory to find that the only object about which we can arrive at some definite conclusions does not appear to meet the general requirements.

One may note that if the acceleration would take place in a hydrodynamical shock at the moment of the SN explosion, whereby particles would be accelerated to the same speed, then one would expect a proton to electron energy ratio of $\sim 10^3$.

In summary, it appears likely that the cosmic rays are produced by a variety of sources. Perhaps different types of sources may also contribute in a diversified way to the various components of the cosmic ray flux. The old arguments which stemmed from the similarity of the spectra between various cosmic ray components as an indication of a common origin may not be as strong as they seemed in the past, since we now know that very similar spectra of particles are produced under completely different astrophysical conditions. At the moment it is not clear whether the cosmic rays can be accelerated in, or near, the sources or whether one has to invoke efficient acceleration mechanisms taking place in the I.S.M., somewhat along the lines which have been discussed this morning in the excellent review paper by Prof. Axford.

As a third point I would like to mention the question of the cosmic ray distribution in the Galaxy. First, let us consider the proton to electron ratio. It was usually assumed that this ratio is constant throughout the Galaxy and equal to ~ 100, the measured value close to the solar system. However, there is at least one argument which casts doubt on this assumption. The argument is as follows: To explain the observed radio emissivity at some properly chosen frequency out to a distance of ~ 1 Kpc from the Sun with the density of electrons present close to the solar system, one needs an average magnetic field of $\gtrsim 10\mu G$.

https://doi.org/10.1017/S0074180900074969 Published online by Cambridge University Press

However, different types of observations indicate that the galactic magnetic field may be only a few μG. Since the galactic synchrotron emission depends on the square of the magnetic field, the density of relativistic electrons in the region we are considering must be about 10 times the measured value close to the solar system (Setti and Woltjer, Astrophys. Lett., 8, 125, 1971). Since it appears impossible to confine cosmic rays with a mean energy density much larger than that close to the Sun, the inference is that the proton to electron ratio is not constant. This, in turn, goes back to the question of the sources discussed above, because it would indicate that the proton and the electron components may have a different origin.

What about the distribution of protons? Are protons essentially produced and accelerated in spiral arms and then diffuse outward in the z-direction much more effectively than along the galactic disk? Is there any difference between the arm and the interarm regions? Arguments based on the study of meteoritic material seem to indicate that there hasn't been much variability (say a factor $\lesssim 2$) in the cosmic ray flux during the past 10^9y, or so. Since in that period of time the Sun moved in and out of the spiral arms several times, this indicates a rather uniform distribution of the protons, at least in the outer regions of the Galaxy. Some evidence in favour of a cosmic ray gradient has been provided by Prof. Wolfendale (this conference), who has shown that perhaps there is an increase of a factor four, or so, going from the outer parts of the galactic disk toward the galactic center. It seems to me that on the basis of the results which have been presented, this conclusion is still premature, although in view of the far reaching consequences the proof of the existence of such gradients would have, one should appreciate every effort spent in trying to establish its reality. The answer to these kinds of questions, of course, relies heavily on the utilization of γ-ray observations, much in the same way as radio observations play a key rôle in understanding the large scale distribution of the electrons. As has been shown during the conference, the interpretation of the galactic γ-ray flux is somewhat controversial. Before one can really use the γ-rays for the diagnosis of the cosmic ray distribution, the rôle played by the discrete sources must be fully settled. These may contribute most of the galactic γ-ray background much in the same way as it happens in the X-ray domain. Observations in the low energy γ-ray region of the e.m. spectrum will also play an important rôle in the understanding of this complicated matter.

As a final point I would like to make a few comments about the hypothesis of an extra-galactic origin of cosmic rays. Although it is quite clear that the cosmic ray nuclei and the electrons are produced and accelerated in the Galaxy, it seems to me that one cannot yet exclude the possibility that protons, and perhaps α particles, which convey most of the cosmic ray energy flux are of extra-galactic origin. The main argument against the extragalactic hypothesis has always been an argument of plausibility, since the energy requirements involved in a universal distribution of cosmic rays appeared too severe to most of the workers in the field. However, on the basis of our present knowledge of the universe and, in particular, on the frequency and strength of the active phases of galactic nuclei, we cannot exclude that the energy requirements for a universal cosmic ray flux can be met. Of course, the electrons which would be accelerated together with the protons in these hypothetical extra-galactic cosmic ray sources must give up all their energy in radiation. If one considers any plausible acceleration mechanisms, one can see that the relativistic electrons must radiate their energy in the far infrared part of the e.m. spectrum where part of the energy density, corresponding to a fraction of 1 eV/cm^3, could still be of non-thermal origin.

Again, a definite answer to this question will be provided by observations in the γ-ray domain. For instance, the limit imposed by the isotropic γ-ray background already tells us that a universal flux of cosmic rays, which most likely would be produced at high redshifts, would imply a low density Universe (present density $\rho_o \lesssim 10^{-7}$ g/cm^3). Also, as has been recalled by Prof. Ginzburg in his introductory talk, the interaction of universal cosmic ray protons with the interstellar gas in the Magellanic Clouds may produce an observable flux of γ-rays. Similar observational situations may be envisaged in the direction of other selected objects. However, the interpretation of the observational data may not be so clearcut, due to the presence of localized γ-ray sources.

Since time is getting short I think I will stop here. The considerations I have made, sometimes in an intentionally provocative way, concern some problems which, I believe, are worth our attention in this very last part of the meeting. Of course, I do not pretend to have made an exhaustive list of the important problems which have been discussed in these past few days, and anyone should feel free to add new topics to the list in the course of the general discussion.