NOTE ON THE ORIGIN OF COSMIC RAYS

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Summary

The question of associating the origin of cosmic rays with properties of highly collapsed stars is discussed. It is shown that the observed intensity of cosmic rays can be explained by means of such an association. The general principles involved in the origin of cosmic rays are briefly considered.

1. It has been suggested that cosmic rays may originate in supernova outbursts.* The question arises as to whether any of the processes discussed in the preceding paper provide support for this suggestion. The values given there in Table I, for the case of a star of mass $10M_\odot$ and an initial rotational velocity before collapse of $1$ km. per sec., would appear to provide a starting-point for such a theory. The values for this case show that instability will not occur until the rotational velocity of the star is of the same order as the velocity of light. Now it is to be expected that in the process of rotational instability the velocity with which the material is thrown off to infinity will be of the same order, but less than, the rotational velocity just before instability occurs. Thus cases may occur in which material is thrown off from a rotationally unstable star with a velocity of the same order as the velocity of light $C$. The kinetic energy possessed by a proton would then be of order $m_p C^2 = 9.3 \times 10^8$ e.V., where $m_p$ is the mass of the proton. That is, the kinetic energy is of the same order as the rest-mass.

It is important to notice that $m_p C^2$ is the average kinetic energy of emitted protons. The discussion given below in Section 3 shows how particles can acquire energies that are considerably in excess of this average value. Indeed it will be seen that $10^9$ e.V. is the basic unit out of which the cosmic rays of very high energy are built. In this connection it may be noted that the observed cosmic ray energy spectrum depends on $E$ according to the factor $dE/E^2$. This shows, for example, that the combined energy of all cosmic rays with energies greater than $10^{15}$ e.V. is less than the combined energy of all cosmic rays with energies greater than $10^{10}$ e.V. by a factor $10^{-10}$. Thus the fraction of the total energy in the form of cosmic rays of very high energy ($> 10^{15}$ e.V.) is extremely small. It follows therefore that the discussion of Section 3 which attempts to explain the origin of these cosmic rays is concerned with very exceptional cases rather than with the average situation.

2. For the above process to occur, the potential $GM/R$ at the surface of the star at the onset of rotational instability must be of order $C^2$. This condition gives

$$\rho = \frac{3C^6}{4\pi G^2 M^2} = 10^{17} \frac{(M_\odot/M)^2}{g} \text{ gm. per cm.}^3,$$

where the mean density $\bar{\rho}$ is defined by $4\pi \rho R^2/3 = M$. Thus provided $M < 30M_\odot$,

the mean density in the star attains a value of order \(10^{14}\) gm. per cm.\(^3\) before the process described in Section 1 occurs. Now at such densities the average distance apart of the particles becomes comparable with the range of nuclear forces. At this stage the whole star passes over into effectively one "atomic nucleus". This nucleus must be almost entirely composed of neutrons, and is similar to the "neutron cores" of Baade and Zwicky.* This result can be understood from the work of the previous paper, which shows that increasing density is characterized by increasing neutron content, and that already at a density of \(10^{14}\) gm. per cm.\(^3\) material must be largely composed of neutrons.

It is important to notice that the cohesive effect of general nuclear forces, existing throughout a star in which \(\bar{\rho} > 10^{14}\) gm. per cm.\(^3\), cannot prevent rotational instability occurring. The reason for this is firstly that owing to the saturation property of nuclear forces the binding energy per neutron in stellar material of density \(10^{14}\) gm. per cm.\(^3\) will not be much different from the value occurring in ordinary atomic nuclei. This gives a binding energy due to nuclear forces that is less than \(10^{-2}C^4\) per gram of material, which is only about one per cent. of the sum of the rotational and gravitational energy of the material. Moreover the nature of nuclear forces is such that the nuclear binding energy cannot be significantly increased by compressing the material to densities higher than \(10^{14}\) gm. per cm.\(^3\).

3. The remarks of the preceding sections indicate that cases occur in which material with density exceeding \(10^{14}\) gm. per cm.\(^3\) is thrown off by rotationally unstable stars. As a result of nuclear transformations and of internal collisions such material will be gradually broken down into protons, neutrons and ordinary laboratory nuclei. But before reaching this final state, the material must pass through an intermediate stage in which it consists largely of nuclear lumps with the following properties:

\[ A \gtrsim 10^6, \quad Z/A \ll 1, \]

where \(Z\) and \(A-Z\) are the numbers of protons and neutrons respectively in the nuclear lumps. It seems possible that a "thunder-storm effect" may occur during this intermediate stage. Thus consider an assembly that consists initially of positively charged nuclear lumps together with a sufficient density of free electrons to preserve electrical neutrality. Then suppose that the nuclear lumps become separated from the free electrons by a process in which the energy required to produce the separation is supplied at the expense of the kinetic energy of the nuclear lumps. On this hypothesis it is clear that large electric potentials must be built up within the distribution of nuclear lumps. The order of magnitude of the largest potential that can arise is given by

\[ Z e V = WA, \]

where \(V\) is the potential attained (taking the potential at infinity as zero) for the special case in which the nuclear lumps all contain \(Z\) protons, \(A-Z\) neutrons, and all have an initial kinetic energy \(WA\).

Consider now the effect of a nuclear transformation resulting in the emission of a proton from one of the nuclear lumps, and let the transformation occur after the charge separation has taken place. The proton must then be repelled by the powerful electric field arising from the whole distribution of positively

* Loc. cit.
charged nuclear lumps, and will reach infinity with a kinetic energy of order $eV$. That is, the proton is repelled to infinity with energy $WA/Z$. Thus, since $A/Z \gg 1$, it follows that such a proton acquires an energy that is large compared with $W$. Now according to Section 1 the quantity $W$ is of order $m_pC^2$, so that the present process results in protons acquiring energies that are large compared with $m_pC^2$. This is what is required to explain the origin of the cosmic rays of very high energy.

It is important to notice that on the present theory the cosmic rays may contain laboratory nuclei as well as protons. For it may well be the case that the nuclear lumps emit these nuclei in addition to protons, and if such nuclei are able to reach infinity without suffering complete break-up due to collisions, then it is to be expected that they will form a component of the cosmic rays.

The above discussion is incomplete in the important respect that the charge separation is not discussed in detail. It would be difficult to give such a discussion, because the motion of material during the process of rotational instability is extremely complicated. For this reason no attempt will be made to specify a definite process. It is of interest, however, to note that charge separation can occur either through the effect of magnetic fields or by motion through a medium that is highly resistant to free electrons, but which allows the nuclear lumps to pass freely. Finally it may be remarked that the conditions described above are only required for the cosmic rays of very high energy. As pointed out in Section 1 these cosmic rays carry a very small fraction of the total energy. Thus the process of charge separation need only be of rare occurrence.

4. The problem of the origin of the cosmic rays is, in its nature, outside the range of laboratory process. In these circumstances the most plausible type of theory is an extrapolation from a process already observed to occur in a less extreme form. The process of rotational instability suggested above fulfils this condition since unstable stars are observed where material is thrown off with velocities of several thousand km. per sec. Thus the difference between the suggested mode of origin of the cosmic rays and the observed process is one of degree rather than of principle. As was seen in the preceding paper the question of degree depends on the initial rotation of the star before collapse begins. If a star with mass appreciably greater than Chandrasekhar’s limit has a sufficiently small initial rotation it seems probable that the required process will occur. Suitably small initial rotations might well occur in about one collapsing star in ten. On the basis of one supernova per nebula per 500 years, the frequency of collapsing stars giving cosmic ray energies may reasonably be taken as one per nebula per 5000 years.

In view of the desirability of obtaining confirmation of the suggestions made above it is fortunate that a calculation can be made, on the basis of the above remarks, for the mean energy density in space of the cosmic rays. As pointed out by Compton and Chou*, if the mean energy density taken throughout space is put equal to the observed energy density in the neighbourhood of the earth, then the total energy of all the cosmic rays in the universe comes out to be considerably larger than the total energy radiated by all the stars in the universe in a time of $10^{10}$ years. An explanation of this remarkable result must evidently be regarded as crucial to any proposed theory of the origin of cosmic rays. This

question has already been remarked on by Baade and Zwicky* but in view of
its great importance it seems worth discussing the matter at greater length than
is given by these authors.

Consider two concentric spheres of radii $r$ and $r + dr$, the centre of the spheres
being at the point where it is desired to calculate the intensity of the cosmic rays.
The number of nebulae lying between the two spheres can be taken as $4\pi r^2 \, dr$,
where $\nu$ is the mean space density of extra-galactic nebulae. The cosmic ray
energy produced by these nebulae is of order

$$4\pi r^2 \, dr \, (M_\odot C^2/\tau) \text{ per sec.,}$$

where $\tau$ is the rate per nebula at which cosmic ray stars occur, and where the
energy produced by each such star is taken as $M_\odot C^2$ (it will be remembered
that these stars all have mass greater than Chandrasekhar's limit). The intensity
of cosmic rays at the centre due to the spherical shell is given immediately on
dividing this expression by $4\pi r^2$ and is accordingly $\nu M_\odot C^2 \, dr/\tau$. The total
cosmic ray intensity is then obtained by integrating the latter expression from
$r = 0$ to $r = R$, where $R$ is the radius of the universe. This gives an intensity

$$\nu M_\odot C^2 R/\tau \text{ per unit area per unit time.}$$

Putting $R = 3 \times 10^8$ parsecs, which is close to the observed radius of the universe
(the values of the radius of the universe indicated by theoretical studies are not
much in excess of $3 \times 10^8$ parsecs), $\nu = 3 \times 10^{-73}$ corresponding to a mean inter-
nebular distance of $5 \times 10^5$ parsecs and $\tau = 1$ cosmic ray producing star per
nebula per 5000 years, gives an intensity of $10^{-8}$ ergs per cm.$^2$ per sec. This
value is in astonishingly good agreement with the observed value of the cosmic ray
intensity for the neighbourhood of the earth.

The above theory relates the following physical quantities:—(i) the cosmic ray
intensity, (ii) the radius of the universe, (iii) the mean internebular distance,
(iv) the frequency of supernovae, by means of a formula involving $C$ and $M_\odot$.
These quantities are of such a diverse nature that this formula could hardly
represent a tautology. Thus the present formula would not appear in a theory
that did not involve collapsing stars. It appears, therefore, that the remarkable
agreement between the calculated and the observed cosmic ray intensities must
be regarded as lending very powerful support to the suggestion that the origin
of cosmic rays is associated with the properties of collapsing stars (the presence
of such a large factor as $10^{-73}$ in the above formula makes it very unlikely that
the agreement is sheer coincidence).

5. The formula obtained in Section 4 for the cosmic ray intensity is based
on the tacit assumption that the point in space at which the intensity is calculated
is not very close to a cosmic ray producing star. It is of interest to estimate how
near such a star the point may be taken before the contribution from the star
rises to a value equal to that calculated above. Let $d$ be the distance from a star
that produces a cosmic ray energy $M_\odot C^2$. If $v_1$, $v_2$ are the greatest and least
velocities respectively (relative to the point in question) of the cosmic rays produced,
then the cosmic rays will reach the point at a time $d/v_2$ after the outburst, and will
continue to pass the point until a time $d/v_1$ after the outburst.† It follows that

* W. Baade and F. Zwicky, loc. cit.
† The outburst itself lasts only a few seconds, as was shown in the previous paper. Thus for
the present purpose the outburst can be regarded as occurring at a definite instant.

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the flood of cosmic rays will last for a time \(d(v_1 - v_2)/v_1 v_2\) and that the mean flux of cosmic ray energy from the star during this time is of order
\[
\frac{v_1 v_2 M \circ C^2}{4\pi d^2(v_1 - v_2)} \text{ per unit area per unit time.}
\]

As an example put \(v_1 - v_2 = 10^{-2}C\), \(v_1 v_2 = C^2\), which gives an intensity of
\[
\frac{10^2 C^3 M \circ}{4\pi d^2} \text{ per unit area per unit time.}
\]

This is equal to the value 10^{-3} ergs per cm.² per sec. obtained in Section 4 when \(d=7 \cdot 10^{22}\) cm. This distance is considerably less than the average distance between the nebulae. It follows therefore that if the cosmic ray intensity due to the star is to rise above the general background produced by the universe as a whole, then the star and the point in question must lie within the same nebula, or in very close neighbours.

The results obtained above may be applied to the Galaxy. Suppose that a cosmic ray producing star occurs at a distance of 10^{22} cm. from the Earth. Then the intensity from the star would become greater than the general background and moreover the angular distribution would become non-isotropic. This effect would last for a time
\[
10^{22}(v_1 - v_2)/v_1 v_2 \simeq 100 \text{ years.}
\]

A comparison of this time with a frequency of one cosmic ray producing star per nebula per 5000 years shows that it is only during comparatively brief periods that the cosmic ray intensity can rise above the general background level discussed in Section 4. This background level remains practically constant over a time interval of order \(R/C\) which is about 3 \cdot 10^8 years when we put \(R=3 \cdot 10^8\) parsecs, and moreover this background level is isotropic, provided the distribution of nebulae at large distances is isotropic.

6. The preceding work concerns one particular process of origin of the cosmic rays. The important question arises as to whether other processes along similar lines can be expected to occur. In particular the idea of a cosmic "thunderstorm effect" would seem worthy of a more general examination. The essential features of the thunderstorm effect are:

(1) The assembly must contain massive charged particles that are of such a nature that their ratio of charge to mass is extremely small compared with \(e/m_p\). Moreover these particles must possess charge of the same sign, and the remainder of the assembly must contain ordinary ionized gas with a sufficient charge bias to compensate for the charge of the massive particles, thereby giving electrical neutrality to the complete assembly.

(2) A process of charge separation occurs that removes the ionized gas and leaves the massive particles. The massive particles must remain charged throughout this process.

(3) An elementary particle (or ordinary atomic nucleus) with charge of the same sign as the charge on the massive particles must be produced within the assembly of massive particles after the charge separation process has taken place. Furthermore, conditions must be such that this particle can move without resistance, thereby enabling the particle to be repelled freely to infinity by the combined electric field of the massive particles.
For the reasons given in Section 4 it is believed that the main energy of cosmic rays arises in processes associated with highly collapsed stars. It is possible, however, that subsidiary effects may occur in many ways. In particular it is possible that subsidiary processes may make an important contribution to the cosmic rays of very high energy, since these cosmic rays carry only a small fraction of the total cosmic ray energy. As an illustrative example we may consider the case of large interstellar dust particles which must become negatively charged if they are situated in a region containing ionized gas.* Under such conditions we have an assembly that satisfies requirement (1). The requirement (2) is also satisfied if it is assumed that the dust particles maintain their charge throughout an encounter between this assembly and a cloud of comparatively dense neutral gas. For if the density of the neutral gas is suitably adjusted the effect of such an encounter is to sweep out the original ionized atoms without appreciably affecting the dust particles. Moreover it can be shown that if the density of the neutral gas is sufficiently high this charge separation process can take place without "lightning flashes" occurring. The requirement (3) cannot be satisfied so long as the dust lies within the neutral gas, but at the end of the encounter when the dust passes out of the neutral gas it is possible for conditions to occur that satisfy this requirement. Thus an electron breaking away from a dust particle at the end of the encounter would be repelled to infinity by the field of the dust particles, and it is easy to show that such an electron can acquire an energy of order $10^{19}$ e.V. without requiring an unduly high density for the large dust particles.

The example given in the previous paragraph involves such simple concepts as to suggest that the principles involved in the origin of cosmic rays may well be very straightforward. Indeed even if some point should on closer investigation be found to render this particular process untenable, the above remarks have significance in that they show the essential simplicity of the "thunder-storm effect" whereas this simplicity is somewhat obscured in the discussion of Section 3 owing to such unusual circumstances as rotational instability and the occurrence of nuclear lumps.