Unfortunately, at the present time only a few underexposed spectra of super-novae are available, and it has not thus far been possible to interpret them.

[1] S. I. Bailey, *Pop. Astr.*, **29**, 554 (1921).
[2] K. Lundmark, *Kungl. Svenska Vetensk. Handlingar*, **60**, No. 8 (1919).
[3] *Handbuch d. Astrophysik*, Vol. VI (Novae).

COSMIC RAYS FROM SUPER-NOVAE

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Communicated March 19, 1934

A. Introduction.—Two important facts support the view that cosmic rays are of extragalactic origin, if, for the moment, we disregard the possibility that the earth may possess a very high and self-renewing electrostatic potential with respect to interstellar space.

(1) The intensity of cosmic rays is practically independent of time. This fact indicates that the origin of these rays can be sought neither in the sun nor in any of the objects of our own Milky Way.

(2) The decrease in intensity of cosmic rays in equatorial regions has successfully been explained by assuming that at least a part of the rays consists of very energetic, positively or negatively charged particles. These particles must be of extra-terrestrial origin, as otherwise the distance traversed by them would not be long enough for the earth's magnetic field to produce the observed dip in intensity at the equator.

From the fact that in the cloud-chamber experiments no protons or charged particles heavier than electrons have been observed in any considerable number, one might conclude that the corpuscular component of cosmic rays consists of positive or negative electrons, or both. The characteristics of the east-west effect indicate that the positively charged particles far outnumber the negatives. However, whether or not these particles are electrons cannot as yet be said with certainty, since the electrons which are observed in cloud chambers may all be secondary particles formed in the earth's atmosphere by different primaries.

With the facts mentioned as a beginning it has become customary to reason approximately as follows. Since none of the objects of our Milky Way seem to produce any cosmic rays, these rays probably are not emitted from any of the extragalactic nebulae either, as the spirals among these nebulae are in most respects similar to our own Milky Way. One arrives therefore at one of two hypotheses, either that cosmic rays originate in intergalactic space or that they are survivors from a time when physical conditions in the universe were entirely different from what they are now (Lemaître). On closer scrutiny both hypotheses prove to be very unsatisfactory. On both views one is forced to assume entirely fantastic processes as regards the mode of creation of the rays. Furthermore, on neither of the two hypotheses can it easily be understood why the ratio of the intensity of cosmic rays to the intensity of visible light from extragalactic space is so much greater than unity, whereas the same ratio for our own galaxy is certainly smaller than one (probably less than 0.005).[1]

In the following we make an entirely new proposal, which, we think, removes some of the major difficulties concerning the origin of cosmic rays.

It has been concluded that extragalactic nebulae cannot be the centers of production of cosmic rays, as no such rays seem to originate in our own galaxy. If, however, the production of cosmic rays is related to some sporadic process, such as the flare-up of a super-nova, the above-mentioned difficulties disappear. We shall try to show that this hypothesis enables us to derive the intensity of the cosmic rays which arrive on the earth, and that direct observations of intensity are in fair agreement with the value thus computed.

B. Intensity of Cosmic Rays.—The considerations of the preceding paper (these PROCEEDINGS, **20,** 254 (1934)) suggest that in order to produce the stupendous radiation of a super-nova each particle of mass m must on the average contribute energy of the order

$$\overline{U} = 0.1\, mc^2, \tag{1}$$

which per proton corresponds to an energy of approximately 10^8 volts. Individual photons or material particles ejected from the super-nova may of course possess energies much greater than $\overline{U}$. We therefore feel justified in advancing tentatively the hypothesis that *cosmic rays are produced in the super-nova process.* It also seems reasonable to assume that a considerable part of the total radiation E_T is emitted in the form of very hard rays or energetic particles. During the passage through the extremely tenuous material parts of the super-nova some of the cosmic rays will be stopped or softened, thus heating up the material of the super-nova to the temperature T. The escape of the cosmic rays must be pictured as a large-scale analogue to the escape of the various hard rays from a radioactive substance with a resulting heating of the substance.

For the purpose of further calculations we assume that cosmic rays are created *only* in super-novae, with the following consequences.

First, it can now be understood why our own galaxy has emitted no cosmic rays during the years in which these rays have been observed.

The reason is simply that no super-nova eruption occurred in our galaxy during this period.

Second, we can estimate the intensity of the cosmic rays reaching the earth, assuming that every super-nova emits in the form of cosmic rays a total amount of energy of the order of E_T. See equation (15) of the preceding paper.

It has previously been shown[1] that, if radiation is emitted uniformly throughout the universe at the constant rate of E ergs/cm.^{3} sec., the intensity of this radiation reaching the earth is

$$\sigma = E\,D/8, \tag{2}$$

where, approximately, $D = 2 \times 10^9$ L.Y. (light years). This formula was derived on the assumption of a red-shift which is proportional to the distance of the source of emission. If the red-shift is caused by an actual expansion of the universe, certain corrections must be applied to the expression (2). These corrections, which do not materially alter our conclusions, may be found in a paper by Professor P. S. Epstein (these PROCEEDINGS, **20,** 67 (1934)).

Since the distribution of nebulae in space corresponds approximately to one nebula in a cube whose edge is $l = 10^6$ L.Y., we obtain

$$\sigma = E_T\,D/8\,l^3\tau, \tag{3}$$

where, in accordance with the observed frequency of occurrence of super-novae in a given nebula, we must put $\tau = 1000$ years. If we insert $E_T = 10^{53}$ to 10^{54} ergs, which according to the preceding paper are probable values of E_T, we obtain

$$\sigma = 0.8 \times 10^{-3} \text{ to } 8 \times 10^{-3} \text{ ergs/cm.}^2 \text{ sec.} \tag{4}$$

The observations of the intensity of cosmic rays made by E. Regener[2] (based on ion counts) give

$$\sigma' = 3.53 \times 10^{-3} \text{ ergs/cm.}^2 \text{ sec.}, \tag{5}$$

whereas Millikan, Bowen and Neher's value[3] is

$$\sigma'' = 3.2 \times 10^{-3} \text{ ergs/cm.}^2 \text{ sec.}, \tag{6}$$

Our hypothesis is therefore in surprisingly good agreement with the direct observations of the intensity of cosmic rays.

Although we ourselves are by no means convinced that the universe is expanding, it must be stated that the above results are not in contradiction with the short time scale of the order of 10^9 years demanded by some of the relativistic cosmologies.

If the initial "spectral" distribution of the cosmic rays leaving a super-nova could be determined, the spectral distribution of the rays reaching the earth could be obtained by taking into account the effect of the red-shift.

If a super-nova should again occur in our Milky Way system, the intensity of the cosmic rays would be considerably altered for the period of a few days. The change in intensity $\Delta\sigma$ would be

$$\Delta\sigma = L_T/4\pi \times 10^{42} r^2 \text{ ergs/cm.}^2 \text{ sec.,} \tag{7}$$

where r is measured in units of 1000 L.Y. Numerically the change is of the order of

$$\Delta\sigma = 10^4/r^2 \text{ ergs/cm.}^2 \text{ sec.,} \tag{8}$$

since, according to the preceding paper, 10^{47} ergs/sec. seems a probable value of L_T. Supposing that the super-nova occurs in the neighborhood of the center of our own galactic system, that is, $r = 30$, approximately, we obtain

$$\Delta\sigma \doteq 11 \text{ ergs/cm.}^2 \text{ sec.} \sim 10^4\ \sigma. \tag{9}$$

If interest in these questions still prevails at that future time, science will therefore be able to test the correctness of our hypothesis some time during the next thousand years or so, as the occurrence of a super-nova in our own system would multiply the intensity of the cosmic rays by a factor one thousand or more. It also seems quite possible to observe with cosmic-ray electroscopes the flare-up of a super-nova in one of the nearer extragalactic nebulae, as for them $r = 1000\ n$, and

$$\Delta\sigma = 0.01/n^2 \text{ ergs/cm.}^2 \text{ sec.,} \tag{10}$$

where n is a number of the order one. It might in this connection be of interest to follow up the causes for Regener's[4] curious balloon observation of March 29, 1933.

Furthermore, we recommend that observers of cosmic rays be on the lookout for short-period systematic increases in the intensity of cosmic rays in order to determine as accurately as possible the time and the direction of the maximum intensity. With such data quickly at hand, astronomers might be able actually to locate the responsible super-nova in one of our near-by systems. As there are about one thousand nebulae in the region

$$0 < n < 10, \tag{11}$$

one super-nova per year should be expected in this "immediate" neighborhood of ours, producing an intensity increase in the cosmic rays of the order of one per cent or more for a period of a few days.

C. Additional Remarks.—A more detailed critical discussion of the views advanced in this article must be postponed because of lack of space. We wish to say only

(1) So far we cannot offer any satisfactory explanation of the east-west effect.

(2) It remains to be explained why the dust and gas clouds which lie along the principal plane of our own galaxy do not appreciably absorb the cosmic rays.[5] This point, however, needs further observational testing.

In addition, the new problem of developing a more detailed picture of the happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the "gravitational packing" energy in a *cold* neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such. The consequences of this hypothesis will be developed in another place, where also will be mentioned some observations that tend to support the idea of stellar bodies made up mainly of neutrons.

D. Conclusions.—From the data available on super-novae we conclude

(1) Mass may be *annihilated* in bulk. By this we mean that an assembly of atoms whose total mass is M may lose in the form of electromagnetic radiation and kinetic energy an amount of energy E_T which probably cannot be accounted for by the liberation of known nuclear packing fractions. Several interpretations of this result are possible and will be published in another place.

(2) The hypothesis that *super-novae emit cosmic rays* leads to a very satisfactory agreement with some of the major observations on cosmic rays.

Our two conclusions are essentially independent of each other and should perhaps be judged separately, each on its respective merits.

[1] F. Zwicky, *Phys. Rev.*, **43,** 147 (1933).

[2] E. Regener, *Zeit. f. Phys.*, **80,** 666 (1933).

[3] R. A. Millikan, I. S. Bowen and H. V. Neher, *Phys. Rev.*, **44,** 246 (1933).

[4] E. Regener, *Nature*, **132,** 696 (1933).

[5] F. Zwicky, *Helvetica Physica Acta*, **6,** 110 (1933).