Investigation of the Close-Pair Effect in Cosmic-Ray Stars by Means of Moving Photographic Plates

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The problem of simultaneity in the creation of close-pair stars has been studied by means of moving photographic plates. It is shown that the so-called "associated" stars are produced at different moments of time.

It has been observed in a number of papers[1-11] that emulsions which have been exposed to cosmic rays contain a larger number of close-lying pairs ($r \ll 1$ mm) of nuclear disintegrations (stars) than is to be expected on the basis of a random spatial distribution. The excess of "close pairs" suggests a clue as to the origin of this effect. It is true, however, that this same effect can arise as a result of a number of experimental factors (cf. Refs. 3, 6, 9, 12) which cannot be evaluated quantitatively without a great deal of difficulty.

The question of whether a close-pair effect does, in fact, exist is therefore of great interest. An approach which would seem capable of resolving this question and which is free from the difficulties referred to above has been indicated in Ref. 10. It is assumed that the close-pair stars differ from stars which are accidently produced in close proximity in that the former are created simultaneously while the latter are created at different moments of time. Hence an investigation of simultaneity would appear to be crucial in the identification of true close-pair stars. In the present work this objective has been realized through the use of moving emulsions as proposed in Refs. 13 and 14.

1. Description of the Method

The work was performed with type *P* emulsions 100 μ in thickness mounted on glass plates with dimensions 58 x 86 ($\pm$ 0.05) mm.

Two plates were superposed with the emulsions lying between them. A clockwork mechanism was used to move the lower plate with respect to the upper one with a velocity of 1 cm in 4 hours. The transverse displacement in this motion did not exceed 100 μ. After a total travel of $\sim$ 1 cm the clockwork mechanism was shut off automatically.

Consider a star produced while the instrument is in operation : if the star has prongs which extend to the surface of the plate, these prongs should have extensions in the other plate. If the distances between the points of egress of the prongs in one plate and the points of entry in the other plate are the same for two close-lying stars, then these stars have been created simultaneously. If this condition is not fulfilled, then the stars have been created at different times and consequently are not related.

The search for prong extensions in the second plate was performed in the following manner. The plates were placed together on the stage of the microscope in exactly the same position they occupied in the holder of the clockwork mechanism before it was set in operation. Both emulsions were scanned together; this is possible at small magnifications (7 x 10 x 1.5 or 7 x 20 x 1.5). When a star of interest was located one of the

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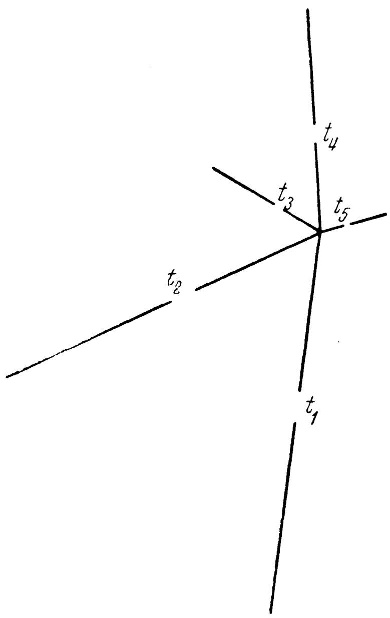

prongs which extended to the surface of the plate was moved to the center of the field in view. Then a strip 500 μ in width and 1 cm in length (in the direction of relative motion of the plates) in the other plate was scanned to find a track running in the same direction as the prong.

For the single-particle density which was observed (690 cm^{-2}) the probability of an accidental coincidence is small. If tracks which are true extensions are neglected, the scanned strip should contain $\sim$ 0.05 tracks running in the appropriate directions (in the plane of the emulsions and depthwise). The possibility of a false coincidence is reduced further if the ionization of the prong is compared with the ionization due to the extension in question. In the case of stars with several (2 or more) prongs which extend to the surface, chance coincidences are virtually impossible.

We now consider the resolving power (with respect to time) of this scheme. When a star has been selected and the extensions of its prongs located, then upon aligning the prongs with the extensions, a picture similar to that shown in the figure is observed. There is a gap t between each prong and its extension caused by the space d between the emulsions; the magnitude of d can be easily determined from the dip angles of the tracks and the gaps t.

We now consider two neighboring stars which might be considered simultaneous on the basis of a preliminary inspection. Having determined the magnitude of d at the site of the first star, it should be possible to predict the points of incidence of the tracks of the second star in the other plate if both stars have been produced simultaneously. The accuracy of this prediction is determined by the length of the track and possible variations in d in going from the site of one star to the other.* Under the conditions of the present experiment this prediction could be made with an accuracy of several (<10) microns corresponding to a resolving power of $(10/10{,}000) \times 240 \approx 0.25$ min.

2. Experimental Results

In 34 plates exposed at a height of 9 km, 2126 stars ** with prong-number $n \gtrsim 2$ were found. A strip 6 mm wide at the edge of the plates was not scanned since large distortions are possible in this region. The remaining area of the plate was divided into sections 1x1 cm in size in which the number of stars was counted. Then all stars lying closer together than $r = 1$ mm were counted. The number of such stars was found to be 113.

For a random spatial distribution the expected number of pairs of stars is

$$p_{\mathrm{stat}} = \sum_{i=1}^{n} \frac{N_i (N_i - 1)}{2} \frac{\pi r^2}{a_i b_i} \left[1 - \frac{4 (a_i + b_i) r}{3\pi a_i b_i} + \frac{2r^2}{2\pi a_i b_i} \right], \tag{1}$$

where n is the number of sections, N_i is the number of stars in the ith section and a_i and b_i are the sides of the ith section.[3] Expression (1) is valid only if the edge effect can be neglected, i.e., for $r \ll a_i, b_i$; this requirement is easily met in the present case. Substituting in (1) the values of the appropriate quantities, we obtain $p_{\mathrm{stat}} = 69$ for $r = 1$ mm. Thus there is an excess of close pairs for distances less than or equal to 1 mm. The size of this effect can be judged from

$$(p_{\mathrm{exp}} - p_{\mathrm{stat}}) / \sqrt{p_{\mathrm{stat}}} = 5.3.$$

The quantity $p_{\mathrm{exp}} - p_{\mathrm{stat}}$ is 44 for $r = 1$ mm; i.e., statistical analysis of our data exhibits a close pair effect approximately the same as that found in Refs. 3 and 6. The existence of this effect has

*This applies only when the stars are produced simultaneously since the magnitude of the space between the plates and the amount of transverse displacement can change during the movement of the plates.

**So-called radioactive stars were not considered.

been shown still more conclusively in Ref. 10 in which not only "doublets" but also "triplets" of close-lying stars were examined. In this work it was shown that two stars separated by a distance less than 300-400 μ were accompanied, as a rule, by a third star located significantly closer than would be expected for a random distribution. Statistical analysis indicates that the probability of obtaining these results on the basis of a random distribution is less than 0.001.

The formation of close pairs may be due to one of the neutrons emitted from the primary star which interacts with a nucleus of the emulsion at a distance $r \lessapprox 1$ mm, thus creating a secondary star. In order to evaluate this effect quantitatively, a count was made of the total number of double stars connected by an ionizing particle (excluding stars which were connected by $\pi-$ mesons which had come to rest). In the plates exposed in this work two double stars were observed out of 2126. In other plates 200, 400, and 600 μ in thickness, which had been scanned for other purposes, there were 5 double stars out of 3828 stars. Converting these figures to hundred-micron plates *** 3.25 double stars were found for 5954 stars, i.e., approximately one double star for every 2000. Thus it follows that one pair of neutron-produced stars is found for approximately 1800 single stars. In this connection it has been assumed that the proton is the connecting particle for all the double stars and that the ratio of the number of neutrons to the number of protons in the elements of the emulsions is 1.2.

The test for the close-pair effect was carried out in 14 pairs of plates containing 2078 stars with prong-number $n \gtrapprox 2$. Determination of the time of creation of the stars requires that at least one of the prongs extend to the surface of the emulsion, i.e., that there be an extension in the other plate. 1600 such stars were observed. Not all of these could be used, however, since a fraction of them (51 %) had been created prior to the exposure of the plates in the apparatus and therefore had no extensions. In addition, some of the stars were produced while the apparatus was being elevated, before the clockwork mechanism was set in operation, and so were not useful in this work (38% of the stars with extensions). The final number of useful stars, i.e., those having extensions and formed while the machine was in operation was found to be $\sim$ 480.

Using the method described in Sec. 2, a search was made for extensions of all stars lying within a distance of 1 mm of each other. Not one pair of simultaneously created stars was found.⁺

3. Discussion of the Results

As has been indicated earlier, statistical analysis shows that the quantity $p_{exp} - p_{stat}$ is equal to 44 for $r = 1000\ \mu$ and 18 for $r = 500\ \mu$. These data converted to 1000 stars are compared below with the results of other authors (the last column refers to the present work):

$$(r \leqslant 0.5 \text{ MM}) \quad 10^3 \cdot \frac{(p_{exp} - p_{stat})}{\Sigma N_i}$$

8.4 [2] 2.9 [3] 18.1 [6] 7.4

$$(r \leqslant 1.0 \text{ MM}) \quad 10^3 \cdot \frac{(p_{exp} - p_{stat})}{\Sigma N_i}$$

— 8.2 [3] 2.4 [6] 20

The number of stars(produced while the instrument was in operation)which have extensions is 480; hence if the close-pair effect does, in fact, exist, the number of simultaneous pairs should be ~ 9 if our data are used and ~ 7.2 if the data of Refs. 3 and 6 are used.

In this experiment not one simultaneous pair of stars was observed. The probability of such a result if an effect of the size given above does really exist is $\sim 10^{-3}$ and $\sim 10^{-4}$ depending on which data are used.

The number of close pairs to be expected from trivial causes (cf. Sec. 2) is 0.27, which does not contradict the results of the experiment.

It should be noted that in calculating the number of stars under our experimental conditions we have not taken account of the change in the prong-number with height. It is known, for instance, that the average number of prongs in a star will increase with height (cf. Ref. 15). If this effect is taken into account the original number of single stars ($\sim$480) should be increased to some extent.

These results show that if the close-pair effect does exist its magnitude is much smaller than is to be expected on the basis of a statistical analysis. This finding agrees with the results of an investigation of the effect carried out with scin-

***This calculation was performed under the assumption that the probability of creation of a secondary star is proportional to the thickness of the emulsion.

⁺The large number of stars produced before the machine was set in operation and the possibility of a transverse displacement of the plates can lead to the appearance of false close-pair stars. In the present case this is of no concern since no simultaneous pairs were found.

[15] Powell, Cameron, et al. Usp. Fiz. Nauk 40, 76 (1950) (Russian translation)

tillation counters,[16] although a detailed comparison of the present results with those would be difficult.

In the above we have proceeded from the entirely reasonable requirement that close-pair stars should be created simultaneously. To be perfectly logical, however, we have not ruled out the possibility that the close pairs are formed with a delay time which is beyond the resolution capabilities of this method. This question can be resolved when a considerably greater amount of experimental data is accumulated. In the event of a negative result, there would seem to be a fundamental contradiction between the statistical analysis and the results of the present work; this would seem to indicate the presence of some methodological error in the statistical analysis. In this connection factors such as nonuniformity of exposure, inhomogeneities in the amount of AgBr, differences in the thickness of the emulsion in different parts of the plates, and the higher counting efficiency in the vicinity of neighboring stars as compared with single stars should be considered. A detailed analysis of these and similar effects should be the subject of a special report.

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On the Theory of Stochastic Processes in Cosmic Radiation

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We study a generalization of the kinetic equation of L. Janossy for the case where the physical quantity $\xi(t)$ does not remain constant between two consecutive jumps, but changes in accordance with some causal law. The equation that is introduced can be successfully applied to various problems concerning stochastic processes in cosmic radiation.

In the present paper we consider some problems of the theory of stochastic processes, which play a very important role in nuclear physics and in the theory of cosmic radiation[1]. We shall not touch upon concrete problems, since there are a large number of papers in this direction in the literature[2]; however, a unified treatment of these problems is lacking.

For the stochastic description of an arbitrary physical process (energy loss, scattering, etc.) we must first of all determine the distribution function of the physical quantities which play a decisive role in the given process. If it is known that the value of some physical quantity $\xi(t)$ at the instant of time t is equal to x, then in certain kinds of stochastic processes (processes without after-effect*) it is easy to determine the probability that the value of the random variable $\xi(\tau)$ is greater than y at any instant of time $\tau \geq t$. Let us designate this probability [the distribution function of the random process $\xi(t)$] by $F(t, x; \tau, y)$. As is well known, the function $F(t, x; \tau, y)$ is determined by two integro-differential equations, introduced by Kolmogoroff[3] and Feller[4].

Let us denote by $P(t, x; y)$ the probability that the random process $\xi(t)$ discontinuously changes its value to $\xi(t+0) \leqslant y$ under the condition that a jump occurred at the instant of time t, and that immediately before the jump $\xi(t-0)$ was

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