[4] The possibility of gaseous crystals in stellar atmospheres has been recently considered by Eddington, *Monthly Notices, Roy. Astron. Soc.*, **88**, 369 (1928).

[5] Debye and Hückel, *Phys. Zeitsch.*, **24**, 185, 305 (1923).

[6] *Bull. Amer. Phys. Soc.*, **3**, 19 (1928).

[7] Langmuir and Mott-Smith, Jr., *General Electric Review*, **27**, 766 (1924). Table XIV.

EVIDENCE THAT THE COSMIC RAYS ORIGINATE IN INTERSTELLAR SPACE

BY ROBERT A. MILLIKAN AND G. HARVEY CAMERON

NORMAN BRIDGE LABORATORY OF PHYSICS, CALIFORNIA INSTITUTE OF TECHNOLOGY

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If it may be regarded as established by the evidence heretofore advanced[1] that the cosmic rays are the signals sent out through the heavens of the creation of the common elements out of positive and negative electrons, the next important question to attempt to answer is "where are these creative processes going on?" To this question there are two different sorts of possible answers, as follows:

(1) In the stars where pressures, densities and temperatures may, one or all, be enormously high, or else

(2) In interstellar space where pressures, densities and temperatures are all extraordinarily low.

In both of these localities matter exists under extreme and as yet unexplored conditions, and in view of the history of the last thirty years of physics, it would no longer be surprising if matter were again found to behave in some hitherto unknown and unexpected way as a new field of observation is entered.

Of the two foregoing alternatives we think it possible to eliminate the first and to establish the second with considerable definiteness, and that for the two following reasons.

First.—If the mere presence of matter in large quantities and at high temperatures favored in any way the atom-building processes which give rise to the cosmic rays, then it is obviously to be expected that the sun, in view of its closeness, would send to the earth enormously more of them than could any other star. But the fact is that all observers are agreed that the change from midday to midnight does not influence at all the intensity of the cosmic rays. This can only mean that *the conditions existing in and about the sun, and presumably also in and about other stars as well, are unfavorable to the atom-building processes which give rise to these rays.*

Since, however, the rays do come to us at all times, day and night, and, according to all observers, at least very nearly equally from all directions—according to some, as accurately as they have as yet been able to make the

measurements—there is scarcely any escape from the conclusion that *the atom-building processes giving rise to the cosmic rays are favored by the conditions existing in interstellar space.* If then, in going from a point in interstellar space toward the center of a star the favorable conditions for atom-building existing in outer space have disappeared as the surface of the star is reached, it is well-nigh inconceivable that they will again reappear in penetrating from the surface to the center—a path along which the changes in physical conditions all continue unchanged in direction. So that from the foregoing we may not only conclude quite definitely that the stars are not the sources of the cosmic rays, but also that the main *atom-building processes probably do not take place inside of stars at all.*

Second.—The foregoing conclusions may also be arrived at from an entirely different mode of approach, namely, from our measurements upon the absorption coefficients and the total energy content of the cosmic rays.

The hardest rays which we have observed are completely absorbed (reduced to say 2% of their initial intensity) in going through 70 meters of water. This means that, even if the atom-building processes went on inside a star, the resulting cosmic radiations could not possibly get out, but would all be frittered away in heat* before emergence, save in the case of those rays that originated in the star's very outermost skin—a skin equivalent in absorbing power to a hundred or so meters of water.

But we have also found that the total energy coming into the earth's atmosphere in the form of cosmic rays is about one-tenth the total heat and light energy coming to the earth from the stars exclusive of the sun.[3] This last fact means that *if the cosmic rays have their origins within the stars they cannot, even at the points of their origin, have an intensity more than ten times that which they have when they reach the earth's atmosphere, for if they had then the cosmic-ray energy transformed into heat by absorption on the way out would yield a total heat outflow from the stars larger than the observed ten to one ratio.* In other words, if the stars are the sources of the observed cosmic rays, it follows from our measurements on absorption coefficients and on total energy content that the total heat output of the stars must be furnished by the atom-building processes going on in their merest outer skins of a thickness equivalent in absorbing power to about a hundred meters of water, and that therefore no atom-building processes, nor any other activities capable of furnishing heat, can then be going on in their interiors.

It is, however, so altogether absurd to suppose that atom-building processes are going on actively at the surface of a star, and down to a depth of a hundred meters, and then suddenly stop there, that we are forced back by this present mode of approach to the same conclusion arrived at from the direct determination of the lack of cosmic-ray activity of a particular star, the sun, namely, to the conclusion that *the observed cosmic rays do not origi-*

nate in the stars at all, but that they must originate under the extreme influences of exactly the opposite sort existing in interstellar or intergalactic space.

These considerations bring us then from two entirely new points of view to the conclusion that the heat output of the stars must be derived from an entirely different source from the atom-building processes which produce the cosmic rays. Jeans[4] and Eddington,[5] from other considerations based wholly upon the lifetimes of the stars, have repeatedly emphasized the necessity of finding a source for this output other and greater than the process of atom-building, but we can now go further and say that the process of energy emission by atom-building does not take place in the stars at all, or at least in such amount as to make the stars an appreciable factor in the output of cosmic rays, for if it did the star would have to be radiating heat much faster than is the case. As is well known, Eddington and Jeans have found this new source of stellar heat *not in an atom-building process, but rather in an atom-annihilating process* which they assume to be going on in the interior of stars, positive electrons being thought to be continually transforming their entire mass into ether waves in accordance with the demands of Einstein's equation. As indicated above, we have sought in vain among our cosmic rays for a ray of penetrating power corresponding to this act. It will be recalled that the mass which disappears in the creation out of hydrogen of one gram-atom of silicon—this produced the hardest cosmic ray that we can say with certainty that we have yet observed, for the iron rays are still to some degree hypothetical—was 0.23 g. The complete annihilation of the mass of hydrogen would obviously then produce, in accordance with Einstein's equation, a ray having approximately 4 times (accurately $\frac{1.0778}{0.23}$ times) the energy and penetrating power of our hardest definitely observed ray. *Our failure to find this ray, however, is no argument at all against the existence of the process in the interior of stars where the pressures are colossal and the densities may be enormous.* Indeed, our failure to find this ray means rather that, if the act occurs at all, as Eddington and Jeans think it must, it is obliged to occur precisely in the interior of stars where the resulting radiation is hidden away behind an impenetrable screen of matter—a screen that transforms all its energy into heat before the ray can get out. If the cosmic rays originated within the stars they would of course be similarly screened.

On the other hand, that the atom-*building* processes responsible for the cosmic rays, as distinct from the atom-*destroying* process just considered, actually occur, as our experiments definitely show, *outside the stars*, or at least where the rays produced by them can get to us, and in an energy that is of the same order of magnitude as that of the heat poured out by the star, is an extraordinarily illuminating fact. For it suggests at once, when combined with Eddington's argument, the following incom-

plete cycle, each element in which now has the *experimental* credentials indicated in the brackets:

(1) Positive and negative electrons exist in great abundance in interstellar space (see the evidence of the spectroscope).

(2) These electrons condense into atoms under the influence of the conditions existing in outer space, viz., absence of temperature and high dispersion (see the evidence of the cosmic rays).

(3) These atoms then aggregate under their gravitational forces into stars (see the evidence of the telescope).

(4) In the interior of stars, under the influence of the enormous pressures, densities and temperatures existing there, an occasional positive electron, presumably in the nucleus of a heavy atom, falls into complete coincidence with a negative, i.e., transforms its entire mass into an ether pulse the energy of which, when frittered away in heat, maintains the temperature of the star and furnishes most of the supply of light and heat which it pours out (see the evidence of the lifetimes of the stars—Eddington-Jeans).

The foregoing is as far as the experimental evidence enables us to go; but the recent discovery of the second element of the above unfinished cycle, namely, that the supply of positive and negative electrons is being used up continually in the creation of atoms, the signals of whose birth constitutes the cosmic rays, at once raises imperiously the question as to why the process is still going on at all after the æons during which it has apparently been in process—or better *why the building stones of the atoms have not all been used up long ago.* And the only possible answer seems to be to complete the cycle, and to assume that these building stones are continually being replenished throughout the heavens by the condensation, with the aid of some as yet wholly unknown mechanism, of radiant heat into positive and negative electrons.

This is a new mode of approach to a conclusion a portion of which at least is old. For the Einstein assumption itself, that mass is convertible into radiant energy, requires the existence also of the inverse process, unless the validity of the Second Law of Thermodynamics, in the form of the principle of microscopic reversibility, is to be denied. The effort to work out the thermodynamics of a cycle containing the Einstein process, but without sacrificing microscopic reversibility, has recently been made by Stern,[6] Tolman,[7] and Zwicky.[8]

But we have in the foregoing gone farther than they. *The essentially new element that we have introduced is the experimental observation that the creative, or atom-building, processes do not appear to take place at all in the stars, but only in interstellar or intergalactic space, where densities and temperatures are practically zero.* Our *experimental* evidence does not, indeed, extend to the creation of the lightest element, hydrogen, out of radiation,

but the inclusion of this also among the creative processes going on only in interstellar space, is a natural extension of our observational data on the other abundant elements. For making this extension we are denying the reversibility at high temperatures and pressures of the process of the transformation of matter into radiation. This is why our conclusion differs from that of Stern, Tolman and Zwicky, and why we are able to regard the universe as in a steady state now, although a state not satisfying the condition of microscopic reversibility.

* It is important to remember that, as we have already shown, rays[2] of this kind become frittered away into heat in this passage through matter *without any change in the quality* (i.e., frequency or absorption coefficient) *of the residual beam.*

[1] Millikan, R. A., and Cameron, G. H., *Proc. Nat. Acad. Sci.*, **14**, 445 (1928).

[2] Millikan, R. A., and Cameron, G. H., *Phys. Rev.*, **28**, 851 (1926).

[3] Millikan, R. A., and Cameron, G. H., *Phys. Rev.*, **31**, 921 (1928).

[4] J. H. Jeans, "Problems of Cosmogony and Stellar Dynamics," Cambridge, **1919**, p. 286.

[5] A. S. Eddington, "The Internal Constitution of the Stars," Cambridge, **1926**, Chap. XI.

[6] Stern, O., *Zeits. Electrochemie*, **31**, 448 (1925).

[7] Tolman, Richard C., *Proc. Nat. Acad. Sci.*, **12**, 67 (1926); **14**, 268, 348, 353 (1928).

[8] Zwicky, F., *Proc. Nat. Acad. Sci.*, **14**, August (1928).

THE DISPLACEMENT INTERFEROMETRY OF BAROMETRIC PRESSURE

BY CARL BARUS

DEPARTMENT OF PHYSICS, BROWN UNIVERSITY

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1. *Apparatus.*—The use of the interferometer U-gauge as a microbarometer reading well within 10^{-4} cm. would seem to be easy of accomplishment; for the apparatus is very simple and the readings sharp and smooth. Actually the investigation is made extremely difficult, since the pressure gauge is also a very sensitive air thermometer. I shall in the following paragraphs show this purposely under varying atmospheric temperature.

A diagram of the apparatus is given in figure 1, in which the shank of the U-gauge, vm, is closed and the other $v'm'$ open to the atmosphere. The mercury mm' is contained in a massive block of iron and the cisterns are about 10 cm. in diameter. As the heads to be observed are relatively small, they may be treated as differentials, $dh = dr \cos\theta$, being the mercury head obtained from the micrometer displacement dr (for an angle of incidence $\theta = 45°$ of the rays to the mirrors), necessary to bring the achro-