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RADIOACTIVITY IN SUPERNOVA REMNANTS

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ABSTRACT

We calculate implications of the idea developed by Burbidge *et al.* that the nearly exponential decrease after the first 100 days of the light-curves of Type I supernovae is due to nuclear energy released by the spontaneous fission of Cf^{254}. Uncertainty of the correctness of the Cf-hypothesis qualifies any interpretation of (1) supernovae light-curves, (2) the location and mechanism of heavy-element nucleosynthesis by rapid neutron captures, and (3) the present-day energy balance in supernova remnants We demonstrate that, if the Cf-hypothesis is correct, the Crab Nebula presently has a radioactive energy input of $1\ 2 \times 10^{36}$ ergs/sec, of which amount 92 per cent is in the form of kinetic energy of heavy ions (5–6-MeV alpha-particles and 60–140-MeV fission fragments). That much energy would be significantly related to observed properties of the nebula. An experimental test of the Cf-hypothesis may be made by searching for gamma-ray lines associated with transbismuth radioactivity The anticipated line spectrum is complex The strongest line flux is $9\ 7 \times 10^{-5}$ cm^{-2} sec^{-1} from the Crab for the 390-keV line of Cf^{249}. Good angular and energy resolution will be required to resolve the lines from the sky background.

I. INTRODUCTION

Burbidge, Burbidge, Fowler, and Hoyle (1957; see also Burbidge, Hoyle, Burbidge, Christy, and Fowler 1956) developed the idea that the roughly exponential decrease (with half-life near 55 days) in the light output observed after the first 100 days following a Type I supernova is due to nuclear energy released by the spontaneous fission of Cf^{254} ($\tau_{1/2}$ = 55 days). Those authors emphasized, on the basis of nuclear physics, that Cf^{254} must be produced with relatively high efficiency by the same mechanism (the *r*-process) that is responsible for the synthesis of the other transbismuth nuclei. The point of view that a Type I supernova is the likely site of *r*-process nucleosynthesis was discussed again by Hoyle and Fowler (1960). They argued, however, that there probably exist about three other beta-stable daughers of *r*-process nuclei which disintegrate by spontaneous fission with half-lives in the range 30–100 days, in which case about $1.5 \times 10^{-4}\ M_\odot$ of Cf^{254} would be required to account for the total energy emitted under the exponential part of the light-curve ($\sim 10^{48}$ ergs). No efficient mechanism for converting fission energy (predominantly kinetic energy of the fission fragments plus gamma rays and beta-particles) into visible light was presented.

Hoyle and Fowler (1960) expressed their concern, however, for the fact that, if the rate of occurrence of Type I supernovae is $(300\ \mathrm{yr})^{-1}$ and if each event synthesizes $1.5 \times 10^{-4}\ M_\odot$ of Cf^{254}, the associated abundances of other nuclei synthesized in the cyclical portion of the *r*-process (e.g., Pt, U) would be expected to be larger by two orders of magnitude than the value observed in solar-system material.

Hoyle, Fowler, Burbidge, and Burbidge (1964) point out that this conflict could be resolved by very long evolution times for Type I supernovae ($\sim 10^{10}$ yr), but they also consider, as an alternative to the Cf-hypothesis, an interpretation based on the damping of an assumed relativistic oscillation in gravitating masses. Unable to resolve this point theoretically, they state: "We urge that observational astronomers turn their attention to the question of which of the two alternatives we have suggested for the light-curves of Type I supernovae is the correct one. Is the source of energy radioactivity or gravitation?"

Seeger, Fowler, and Clayton (1965) found that the simultaneous production of the first two *r*-process peaks (A = 80 and A = 130) requires an environment characterized by $T = 2.43 \times 10^9\ ^\circ$K and $n_n = 5 \times 10^{26}$ cm^{-3} lasting for a time $\Delta t \simeq 4$ sec. With the additional assumption that an adequate ratio of neutrons/seed nuclei can be obtained only by an adiabatic expansion following the iron-helium phase change that occurs in massive-star core implosions, those authors also showed that the necessary environment occurs in stars of about 10^5 $M_\odot$—hardly a Type I supernova. They also demonstrated that the fission cycle in the *r*-process, which is the part responsible for the transbismuth nuclei, occurs in an altogether different environment—$T \simeq 1 \times 10^9$ and $N_n \simeq 3 \times 10^{25}$ cm^{-3}. It could, in principle, occur in physically distinct objects with a different neutron source as well. It is a possibility, then, that the "long-time" solution responsible for the transbismuth nuclei occurs in Type I supernovae, whereas the first two peaks may be synthesized in massive objects. The answer to this question can only come from following in detail the nuclear history of each mass element of a supernova explosion—a difficult task even with the aid of modern computers. Unable to answer this question, Seeger *et al.* say: "It becomes increasingly important to have some independent evidence for locating the *r*-process site, whether massive objects, conventional supernovae, or both."

The experimental observation of nuclear gamma rays associated with transbismuth radioactivity in supernova remnants would present such independent evidence. If the Cf^{254} hypothesis is correct or if the site of *r*-process nucleosynthesis (at least the long-time part) is Type I supernovae, there must be a characteristic spectrum of line gammas emanating from their remnants. It is the purpose of this paper to estimate the anticipated flux and spectrum from the Crab remnant, which will probably be the easiest remnant to observe. The remnant age of 910 years is also a favorable age for observation, since it is old enough to have a relatively simple spectrum yet young enough to have a large variety of radioactivities still present. It is interesting to note, however, that, if the X-ray source discovered in the constellation Scorpius by Giacconi, Gursky, Paolini, and Rossi (1962; see also Bowyer, Byram, Chubb, and Friedmann 1964) is a Type I remnant, the associated nuclear gamma-ray flux may well exceed that from the Crab by an order of magnitude.

II. THE RADIOACTIVE DECAY SCHEMES

Detailed evaluations of the mechanisms of *r*-process nucleosynthesis have been made by Burbidge *et al.* (1957) and by Seeger *et al.* (1965). They find that nuclei are synthesized in the event up to $Z = 93$, at which point neutron-induced fission terminates the addition process. These nuclei lie far to the neutron-rich side of beta-stability and include masses up to $A \simeq 270$. As the heaviest of these begin beta-decay toward the stability line, however, the associated increase in charge causes them to become unstable to spontaneous fission. In this way it has been argued that all the *r*-process nuclei synthesized with atomic weights $A > 255$ undergo spontaneous fission rather than chains of alpha-decay. That point of view will also be adopted here, with the additional assumption that all the fission half-lives of beta-stable species with $A > 255$ are sufficiently short that they play no *present-day* role in the Crab Nebula. However, Hoyle and Fowler (1960) have pointed out that the results of Johansson (1959) introduce considerable doubt that the fission half-lives of beta-stable species with neutron number $N \geq 156$ are all shorter than, say, 100 years. It may thus be appropriate to point out that, if there are any such beta-stable nuclear species *produced* in the *r*-process, they are neglected in this paper. This reservation is stated explicitly because spontaneous fission is an appreciable source of both gamma rays and kinetic energy.

The picture we have adopted for the transbismuth radioactivity in the Crab, then, is the following: *The* r*-process mechanism synthesized* R_A *nuclei of atomic weight A in the explosion, and all nuclei for which* $A > 255$ *have already undergone spontaneous fission.* Note that the R_A's, as defined here, are not functions of time, but are the numbers of nuclei of atomic weight A originally produced. The heavy radioactive nuclei characterized by the production-curve R_A began radioactive decay in the Crab Nebula 910 years ago. Species with short half-lives (say $\tau_{1/2} < 100$ yr) will no longer be important in the Crab unless they are daughters of longer-lived activities. Thus the radioactivities usually discussed in connection with the light-curve (e.g., Cf^{254}, Fe^{59}) are not the relevant ones for the present-day radiation in the Crab. The long-lived radioactivities like U and Th, although they may be in considerable abundance in the Crab, also have low specific activity due to their very low decay rates. As is well known, the originally produced nuclear species having half-lives near the age of the Crab are the ones presently making the largest number of decays per unit time in the remnant.

It is no problem to write explicit solutions to the decay chains. Each abundance R_{A} serves as the source for a series of beta- and alpha-decays (barring fission), ending ultimately at Pb or Bi. Let the nuclear species occurring in each chain be enumerated in order of occurrence by an integer $k = 1, 2, \ldots$, and let the abundance of the kth number of the chain starting from atomic weight A be designated $N_k^{\text{A}}(t)$. Let the radioactive decay rate of species k be λ_k. Then the differential equations for *that particular chain* are

$$\frac{dN_1^{\text{A}}}{dt} = -\lambda_1 N_1^{\text{A}}, \qquad \frac{dN_k^{\text{A}}}{dt} = -\lambda_k N_k^{\text{A}} + \lambda_{k-1} N_{k-1}^{\text{A}}, \qquad k > 1, \tag{1}$$

with boundary conditions

$$N_k^{\text{A}}(0) = \begin{cases} R_{\text{A}}, & k = 1 \\ 0, & k > 1 \end{cases}.$$

The solution for the chain abundances is due to Bateman (1910):

$$N_k^{\text{A}}(t) = R_{\text{A}} \sum_{i=1}^{k} C_{ki}^{\text{A}} e^{-\lambda_i t}, \tag{2}$$

where

$$C_{ki}^{\text{A}} = \frac{\lambda_1 \lambda_2 \lambda_3 \ldots \lambda_{k-1}}{(\lambda_k - \lambda_i)(\lambda_{k-1} - \lambda_i) \ldots (\lambda_2 - \lambda_i)(\lambda_1 - \lambda_i)}, \qquad \text{omitting} \left(\frac{1}{\lambda_i - \lambda_i}\right).$$

From this solution for each chain, the abundance of any species at the present time may be found, but it is necessary to take into account that any particular nuclear species may be contributed to by more than one chain. For instance, the species Ra^{226} is the $k = 1$ member of the chain starting at A = 226, the $k = 2$ member of the chain starting at A = 230 (Th^{230}), the $k = 5$ member of the chain starting at A = 234 (Th^{234}), etc. Thus the present abundance of Ra^{226} is the sum of the appropriate terms of each chain that pass through Ra^{226}. In this manner, the abundance of each radioactive species $N(\text{A}, Z, t)$ may be computed for any age t.

III. THE GAMMA-RAY LINE SPECTRUM

Let $\epsilon(\nu, \text{A}, Z)$ be the fraction of decays of species (A, Z) that is followed by the emission of a prompt gamma ray of frequency ν. Then the total number of nuclear gamma rays of frequency ν emitted per unit time by the nebula is

$$N(\nu) = \sum_{\text{A}, Z} \epsilon(\nu, \text{A}, Z) \lambda_{\text{A}, Z} N(\text{A}, Z, t). \tag{3}$$

In actual practice it is seldom necessary to use the full numerical complexity of equation (2). Those mass chains for which the early members have half-lives much shorter that the remnant age quickly decay to the first relatively long-lived member of the chain. Thus the initial abundance R_{A} may, with high accuracy, be considered as transferred entirely to the first long-lived member of the chain. The short-lived daughters of long-lived parents, on the other hand, are usually in equilibrium with their parents, in which case the rate of daughter decays is equal to the rate of parent decays (within any *one* chain). These physical approximations have been made only when warranted by their high accuracy, but the resulting simplification in the calculations has been considerable.

Since the relevant half-lives are reasonably well known, it is evident from equations (2) and (3) that the expected gamma spectrum involves three distinct calculations: (1) the calculation of the *r*-process production-curve, R_A, (2) the calculation of the product $\lambda_{A,Z} N(A, Z, t)$ in terms of the set R_A, and (3) the estimate of the numbers and energies $\epsilon(\nu, A, Z)$ of gamma rays emitted per average decay of species (A, *Z*).

1. *The* r-*Process Production-Curve*, R_A

The essential point of this paper is to point out that the *r*-process production-curve, R_A, upon which so many theoretical arguments hinge, may, in part, be measurable by recording the line spectrum of gamma rays from the supernova remnant. The possibility of this detection was pointed out to us by Dr. R. C. Haymes. All workers in the field have recognized the fact that the details of the production-curve are not calculable at our present state of nuclear knowledge. Seeger *et al.* have emphasized that this situation is especially acute for the transbismuth nuclei, although their conclusion was that the shape of the production-curve is likely to be in good agreement with the earlier calculations of Burbidge *et al.* And even if the shape of R_A could be calculated with accuracy, the attribution of the process to Type I supernovae and the absolute yield of each event are highly uncertain. We therefore regard the measurement of the gamma-ray line spectrum of the Crab as a potential means of determining (1) if the Cf-hypothesis is the correct explanation of the light-curves or (2) if Type I supernovae are the site of the *r*-process even if the yield is inadequate to explain the light-curve as a result of the fission hypothesis.

TABLE 1

THE *r*-PROCESS PRODUCTION-CURVE R_A*

A	R_A (Atoms × 10^{-50})	A	R_A (Atoms × 10^{-50})
255	7 1	240	5 6
254	7 1	239	14
253	9 6	238	21
252	5 0	237	32
251	12	236	8 5
250	7 1	235	34
249	7 1	234	4 3
248	12	233	4 3
247	5 3	232	33
246	5 3	231	6 5
245	22	230	6 3
244	20	229	1 6
243	8 0	228	1 6
242	13	227	1 6
241	11	226	2 3

* The *r*-process yields of each supernova in units of 10^{50} atoms are taken from Table VIII.1 of Burbidge *et al* (1957), and normalized to 1 5 × 10^{-4} $M_\odot$ of Cf^{254}.

As a working model to estimate the likely shape of the gamma spectrum and the quality of an experiment that must be performed to measure that spectrum, we assume the following: (*a*) the shape of the production-curve is given by Table VIII.1 of Burbidge *et al.* (1957), and (*b*) the absolute yield of Cf^{254} necessary to account for the light-curve is $1.5 \times 10^{-4} M_\odot$ (Hoyle and Fowler 1960). Table 1 lists the number of atoms R_A produced by the Crab for those atomic weights which contribute appreciably to the present-day radioactivity if these two assumptions are correct.

It is also appropriate at this point to estimate R_A by replacing assumption (*b*) above by the following assumption: (b') all of the heavy r-process abundances observed in the solar system were synthesized in Type I supernovae that exploded before the formation of the solar system. To make this estimate as simply as possible, we will assume that, at the time the solar system formed, the Galaxy consisted of 10^{11} $M_\odot$ having composition identical to that of the solar system. Seeger *et al.* (1965) showed that the solar-system abundances of the elements Os, Ir, and Pt synthesized by the r-process are

$$\frac{(\mathrm{Os}+\mathrm{Ir}+\mathrm{Pt})_r}{\mathrm{Si}}=\frac{0.55+0.29+0.85}{10^6}=1.69\times 10^{-6}\ \text{atoms/Si atom}.$$

The existence of this amount throughout the Galaxy when the solar system formed would have corresponded to 730 $M_\odot$ of Os + Ir + Pt created by the r-process. Again referring to Table VIII.1 of Burbidge *et al.* we see that the production of 730 $M_\odot$ of Os + Ir + Pt by the r-process is accompanied by the production of 49 $M_\odot$ of Cf^{254}. The amount of Cf^{254} that must have been produced by each supernova would then be 49 $M_\odot$ divided by the total number of Type I events in the Galaxy in the period between its formation and the formation of the solar system. If the average rate of occurrence of Type I events is Λ_{sn}, and if the appropriate interval of time over which the events had been occurring is T_{sn}, then the number of contributing supernovae is $N_{\mathrm{sn}} = \Lambda_{\mathrm{sn}}\, T_{\mathrm{sn}}$. A rough estimate of the number of supernovae may be obtained by using two commonly quoted values, $\Lambda_{\mathrm{sn}} = (300\ \mathrm{yr})^{-1}$ and $T_{\mathrm{sn}} = 10^{10}$ yr. Then $N_{\mathrm{sn}} \simeq 3.3 \times 10^7$, whereupon the yield of each supernova becomes 1.5×10^{-6} $M_\odot$ of Cf^{254}. It will be noticed that this yield is exactly 100 times smaller than the one we have assumed to be required to explain the light-curve by spontaneous fission. *Thus Type I supernovae may be the site of* r-*process nucleosynthesis even if the* Cf^{254} *light-curve hypothesis is incorrect.* If that is the case, the values of R_{A} in Table 1 must all be reduced by a factor of 100. This means that an experiment designed to check the r-process mechanism for the Crab must be 100 times as sensitive as one required to check the light-curve hypothesis. Of course, the number of effective supernovae may be considerably different than 3.3×10^7. The value of either Λ_{sn} or T_{sn}, or both, may be ill chosen. Hoyle and Fowler (1960) observed that Type I supernovae may require long evolution times, in which case the interval of time over which they explode is considerably less than the entire galactic time span with the net result that the r-process yield of each event must be increased. Alternatively, one could claim that the solar system *did not* form from a "well-mixed" or "average" sample of galactic gas. If the solar system is deficient in its admixture of the average 3.3×10^{-4} supernovae per solar mass, the r-process yield of average supernovae will also be underestimated. Ninety per cent of the solar abundance of Eu is due to the r-process mechanism (Seeger *et al.* 1965), and it is probably the best indicator of r-products in stellar atmospheres. We find no indication of a solar deficiency in Eu, and thus consider the deficiency possibility unlikely. One measurement may be invaluable in narrowing the range of possibilities for r-process nucleosynthesis. But for the purpose of trying to estimate the requirements of such an observation, we will assume that R_{A} is given by Table 1 if the light-curve hypothesis is correct and by 10^{-2} times if only the r-process location in Type I events is correct. Needless to say, R_{A} is zero if the r-process does not occur in Type I supernovae at all.

2. *Calculation of* $\lambda_{A,Z}\,\mathrm{N}(A, \mathrm{Z}, \mathrm{t})$

We have already outlined the procedure for the calculation of $N(\mathrm{A}, Z, t)$. The number of decays per unit time of each species, which is a linear measure of the intrinsic importance of each activity, is given by $\lambda_{\mathrm{A},\,Z}\, N(\mathrm{A}, Z, t)$. We have computed that product for those species that may have significant specific activity today. The results are given in Table 2. We have shown the explicit dependence of the present abundances upon the production-curve R_{A} to facilitate evaluation of the abundances for any assumed production-curve. (Chains contributing $< 10^{-3}$ of the present abundance are ignored.) The third

TABLE 2

Present Decay Rates in Crab Nebula*

Nuclide	Present Abundance	dN/dt (sec^{-1})
Cf^{251}	$4\ 55\times10^{-1}\,(R_{251}+R_{255})$	$2\ 4\times10^{40}$
Cm^{250}	$9\ 70\times10^{-1}\,R_{250}$	$7\ 6\times10^{38}$
Cf^{249}	$1\ 74\times10^{-1}\,(R_{249}+R_{253})$	$1\ 8\times10^{40}$
Cm^{248}	$9\ 99\times10^{-1}\,(R_{248}+R_{252})$	$7\ 9\times10^{37}$
Cm^{247}	$5\ 45\times10^{-1}\,(R_{251}+R_{255})+1\ 00\,R_{247}$	$8\ 6\times10^{35}$
Cm^{246}	$8\ 97\times10^{-1}\,R_{246}$	$1\ 8\times10^{39}$
Cm^{245}	$7\ 91\times10^{-1}\,(R_{249}+R_{253})+9\ 34\times10^{-1}\,R_{245}$	$8\ 0\times10^{39}$
Pu^{244}	$1\ 00\,R_{244}$	$5\ 8\times10^{35}$
Pu^{243}	$7\ 8\ \times10^{-12}\,(R_{251}+R_{255})+1\ 43\times10^{-11}\,R_{247}$	$8\ 7\times10^{35}$
Am^{243}	$9\ 21\times10^{-1}\,R_{243}$	$2\ 2\times10^{39}$
Pu^{242}	$1\ 03\times10^{-1}\,R_{246}+9.98\times10^{-1}\,R_{242}$	$8\ 0\times10^{37}$
Pu^{241}	$1\ 10\times10^{-3}\,(R_{249}+R_{253})+1\ 31\times10^{-3}\,R_{245}$	$8\ 0\times10^{39}$
Am^{241}	$2\ 53\times10^{-1}\,R_{241}+3\ 5\times10^{-2}\,R_{245}+2\ 1\times10^{-2}\,(R_{249}+R_{253})$	$1\ 9\times10^{40}$
U^{240}	$2\ 12\times10^{-11}\,R_{244}$	$5\ 8\times10^{35}$
Np^{240}	$5\ 13\times10^{-13}\,R_{244}$	$5\ 8\times10^{35}$
Pu^{240}	$9\ 11\times10^{-1}\,R_{240}$	$1\ 7\times10^{39}$
Np^{239}	$7\ 78\times10^{-7}\,R_{243}$	$2\ 2\times10^{39}$
Pu^{239}	$9\ 74\times10^{-1}\,R_{239}+7\ 8\times10^{-2}\,R_{243}$	$1\ 3\times10^{39}$
U^{238}	$1\ 00\,R_{238}$	$1\ 0\times10^{34}$
Np^{237}	$1\ 00\,R_{237}+7\ 5\times10^{-1}\,R_{241}+3\times10^{-2}\,R_{245}+1\times10^{-2}\,(R_{249}+R_{253})$	$4\ 2\times10^{37}$
U^{236}	$1\ 00\,R_{236}+9\times10^{-2}\,R_{240}$	$8\ 4\times10^{35}$
U^{235}	$1\ 00\,R_{235}+3\times10^{-2}\,R_{239}$	$1\ 1\times10^{35}$
U^{234}	$9.97\times10^{-1}\,R_{234}$	$3\ 8\times10^{37}$
Pa^{233}	(Equil. with Np^{237})	$4\ 2\times10^{37}$
U^{233}	$9\ 96\times10^{-1}\,R_{233}$	$4\ 8\times10^{37}$
Th^{232}	$1.00\,R_{232}$	$5\ 1\times10^{33}$
Th^{231}	(Equil with U^{235})	$1\ 1\times10^{35}$
Pa^{231}	$9\ 81\times10^{-1}\,R_{231}$	$4\ 3\times10^{38}$
Th^{230}	$9\ 92\times10^{-1}\,R_{230}+3\times10^{-3}\,R_{234}$	$1\ 8\times10^{38}$
Th^{229}	$9.17\times10^{-1}\,R_{229}+4\times10^{-3}\,R_{233}$	$4\ 6\times10^{38}$
Ac^{227}	(Equil with Pa^{231})	$4\ 3\times10^{38}$
Th^{227}	(Ac^{227} β^-; 98.8%)	$4\ 2\times10^{38}$
Ra^{226}	$6.78\times10^{-1}\,R_{226}+7\times10^{-3}\,R_{230}$	$2\ 2\times10^{39}$
Ra^{225}	(Equil. with Th^{229})	$4\ 6\times10^{38}$
Ac^{225}	(Equil. with Th^{229})	$4\ 6\times10^{38}$
Fr^{223}	(Ac^{227} α; 1 2%)	$5\ 2\times10^{36}$
Ra^{223}	(Equil. with Pa^{231})	$4\ 3\times10^{38}$
Rn^{222}	(Equil. with Ra^{226})	$2\ 2\times10^{39}$
Fr^{221}	(Equil. with Th^{229})	$4\ 6\times10^{38}$
Rn^{219}	(Equil. with Pa^{231})	$4\ 3\times10^{38}$
Po^{218}	(Equil. with Ra^{226})	$2\ 2\times10^{39}$
At^{217}	(Equil. with Th^{229})	$4\ 6\times10^{38}$
Po^{215}	(Equil. with Pa^{231})	$4\ 3\times10^{38}$
Pb^{214}	(Equil. with Ra^{226})	$2\ 2\times10^{39}$
Bi^{214}	(Equil. with Ra^{226})	$2\ 2\times10^{39}$
Po^{214}	(Equil. with Ra^{226})	$2\ 2\times10^{39}$
Bi^{213}	(Equil. with Th^{229})	$4\ 6\times10^{38}$
Po^{213}	(Bi^{213} β^-; 98%)	$4\ 5\times10^{38}$
Pb^{212}	(Equil. with Th^{232})	$5\ 1\times10^{33}$
Pb^{211}	(Equil. with Pa^{231})	$4\ 3\times10^{38}$
Bi^{211}	(Equil. with Pa^{231})	$4\ 3\times10^{38}$
Pb^{210}	(Equil. with Ra^{226})	$2\ 2\times10^{39}$
Bi^{210}	(Equil. with Ra^{226})	$2\ 2\times10^{39}$
Po^{210}	(Equil. with Ra^{226})	$2\ 2\times10^{39}$
Tl^{209}	(Bi^{213} α; 2%)	$9\ 2\times10^{36}$
Pb^{209}	(Equil. with Th^{229})	$4\ 6\times10^{38}$
Tl^{207}	(Equil with Pa^{231})	$4\ 3\times10^{38}$

* Daughters of U^{238} and Th^{232} making less than 10^{35} decays/sec have been omitted

column of Table 2 gives the present rates of decay for the values of R_A assumed in Table 1.

3. *Estimates of* $\epsilon(\nu, A, Z)$

The knowledge of the gamma-ray spectrum emitted promptly after each decay is imperfectly known. It is predominantly the prominent energetic lines that have been accurately identified and whose probabilities of occurrence per average decay are known. Accordingly we choose to list in Table 3 the prominent lines by their energy and by the percentage of decays resulting in that line. The major source of such information is the Landolt-Börnstein (Hellwege 1961) compilation of nuclear-energy levels. All sources used are listed as footnotes to Table 3. Estimates made by us are preceded by approximate equality signs. When a detailed gamma-ray spectrum of a supernova remnant is obtained, it will be advisable, of course, to check the then-available primary sources for the relevant branching ratios. The fluxes at the Earth for each line are given in the fourth column, wherein we have ignored absorption and assumed a distance of 3500 light-years for the Crab Nebula. The composite line spectrum is displayed in Figure 1. This figure shows all nuclear lines with anticipated fluxes greater than 10^{-7} cm^{-2} sec^{-1}.

It will be an invaluable aid to the understanding of supernovae and their role in nucleosynthesis if it can be determined whether such fluxes originate from the Crab. The intrinsic limitation to performing such a measurement depends on the background of the sky. Arnold, Metzger, Anderson, and Van Dilla (1962) have made the only extra-atmospheric measurements to date of the continuous photon flux in the energy range of hundreds of keV. Using a Cs I phoswich counter in the Ranger 3 spacecraft, they observed a photon flux below 1 MeV that is well approximated by $dN/dE = 1.2 \times 10^{-5} E_6^{-7/4}$ cm^{-2} sec^{-1} keV^{-1} srad^{-1}, where E_6 is the photon energy in MeV. Since this omnidirectional flux is, over the whole energy region involved, much greater than the line fluxes of Figure 1, it is quite obvious that detection of these lines will require a gamma-ray telescope of small solid angle and high energy resolution. Figure 2 is an example of how the spectrum would appear for two differing telescopes: (*a*) one with energy resolution of 20 keV and solid angle of 0.1 srad, and (*b*) one with energy resolution of 5 keV and solid angle of 0.01 srad. This figure is intended to demonstrate that the experimental check is a technical possibility, but that good resolution will be required to make the lines stand out.

IV. SPONTANEOUS FISSION

Spontaneous fission is a prolific source of both kinetic energy and gamma rays, and hence must be considered as potentially important even today in the Crab Nebula. The majority of the gammas lie in a continuous spectrum rather than in lines. Smith, Fields, and Friedman (1956) have found that the average spontaneous fission of Cf^{252} is accompanied by the prompt emission of 10.3 gammas having total energy of 8.2 MeV, whereas Bowman and Mann (1955) measured 12 gammas/fission having total energy of 14 MeV for the same decay. We tentatively adopt the more complete measurements of Smith *et al.* The measured gamma spectrum is a continuous one rising sharply to a maximum near 100 keV and decreasing for energies greater than 100 keV approximately like $n_\gamma(E)dE \simeq [1.5 \times 10^{-(2+E/1800)}$ gamma/fission $-$ keV$]dE$. We have assumed that these features are common to all fission events.

Also emitted in fission events are gammas of characteristic energies that are, however, difficult to predict. The fission fragments lie to the neutron-rich side of beta-stability and must make, on the average, six beta-decays/fission to achieve stability. An average heavy-element beta-decay is accompanied by about one gamma ray with energy generally between 200 keV and 2.5 MeV. Since the fission fragments themselves define a doubly peaked mass spectrum, we believe that no significant effect is overlooked by assuming that a spontaneous fission event is accompanied by six delayed gammas with a flat continuous spectrum between 0.2 and 2.5 MeV. Griffin and Glendenin (1964) also

TABLE 3

LINE GAMMA FLUXES AT EARTH FROM CRAB NEBULA*

Nucleus	E_γ (MeV)	Branch (Per Cent)	Flux ($cm^{-2}\ sec^{-1}$)
Cf^{251}	0 18	10†	$1\ 9\times10^{-5}$
Cf^{249}	0 39	75‡	$9\ 7\times10^{-5}$
	0 34	15	$2\ 0\times10^{-5}$
	0 26	3	$3\ 9\times10^{-6}$
Cm^{245}	0 17	14‡	$8\ 1\times10^{-6}$
	0 13	5	$2\ 9\times10^{-6}$
Am^{243}	0 075	60§	$9\ 4\times10^{-6}$
Am^{241}	0 06	40§	$5\ 7\times10^{-5}$
Np^{239}	0 28	30‡	$4\ 6\times10^{-6}$
	0 23	31	$4\ 8\times10^{-6}$
	0 10	24	$3\ 7\times10^{-6}$
	0 057	30	$4\ 6\times10^{-6}$
Pa^{231}	0 30	~ 8‡	$2\ 5\times10^{-7}$
Th^{229}	0 087	~80‡	$2\ 7\times10^{-6}$
Th^{227}	0 334	5 2‡	$1\ 6\times10^{-7}$
	0 256	7 1	$2\ 2\times10^{-7}$
	0 236	10 6	$3\ 4\times10^{-7}$
	0 113	4 2	$1\ 3\times10^{-7}$
	0 080	4 6	$1\ 4\times10^{-7}$
	0 060	9	$2\ 9\times10^{-7}$
	0 050	13 6	$4\ 4\times10^{-7}$
	0.032	12	$3\ 7\times10^{-7}$
	0 030	27	$8\ 4\times10^{-7}$
Ra^{226}	0 187	4‖	$6\ 4\times10^{-7}$
Ac^{225}	0 099	~10‖	$3\ 3\times10^{-7}$
Ra^{223}	0 338	4 2‡	$1\ 3\times10^{-7}$
	0 324	4 9	$1\ 5\times10^{-7}$
	0 270	21 4	$6\ 6\times10^{-7}$
	0 154	28	$8\ 7\times10^{-7}$
	0 144	19	$5\ 9\times10^{-7}$
	0 122	11	$3\ 4\times10^{-7}$
Fr^{221}	0 22	14‡	$5\ 0\times10^{-7}$
Rn^{219}	0 40	4 8‡	$1\ 5\times10^{-7}$
	0 27	8 6	$2\ 7\times10^{-7}$
Pb^{214}	0 352	40§	$6\ 3\times10^{-6}$
	0 295	20	$3\ 2\times10^{-6}$
	0 24	8	$1\ 3\times10^{-6}$
	0 18	4	$6\ 3\times10^{-7}$
Bi^{214}	0 61	47§	$7\ 4\times10^{-6}$
	1 12	20	$3\ 2\times10^{-6}$
	1.76	25	$4\ 0\times10^{-6}$
Bi^{213}	0 44	10†	$3\ 2\times10^{-7}$
Bi^{211}	0.35	~17	$5\ 3\times10^{-7}$

* Assuming production-curve of Table 1 and distance to Crab of 3500 light-years

† Assumed 10 per cent.

‡ Landolt-Börnstein (Hellwege 1961).

§ S A Reynolds (private communication)

‖ Adams and Lowder (1964).

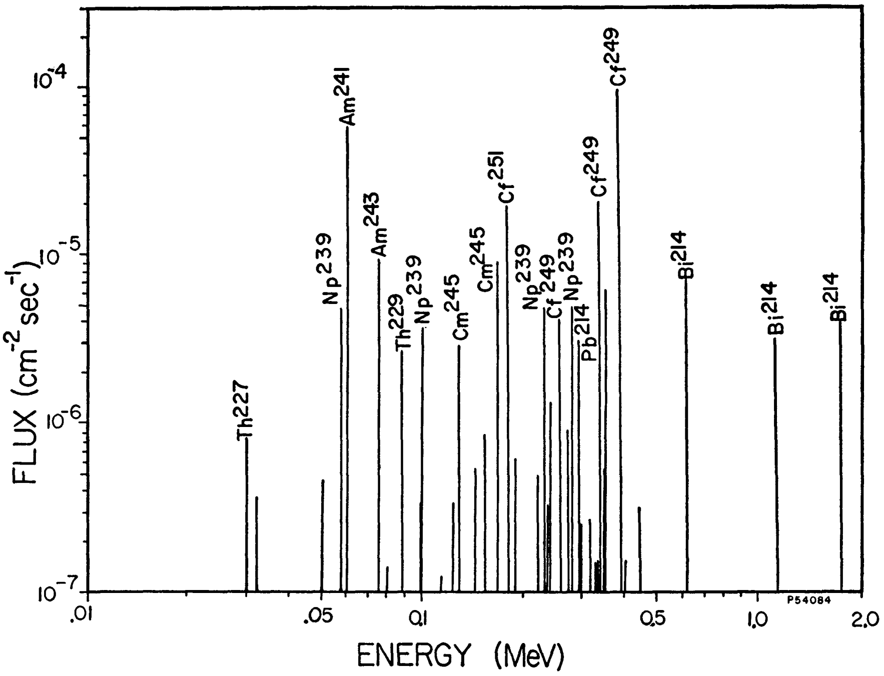

FIG. 1 —Spectrum of line fluxes anticipated from the Crab Nebula (taken from Table 3)

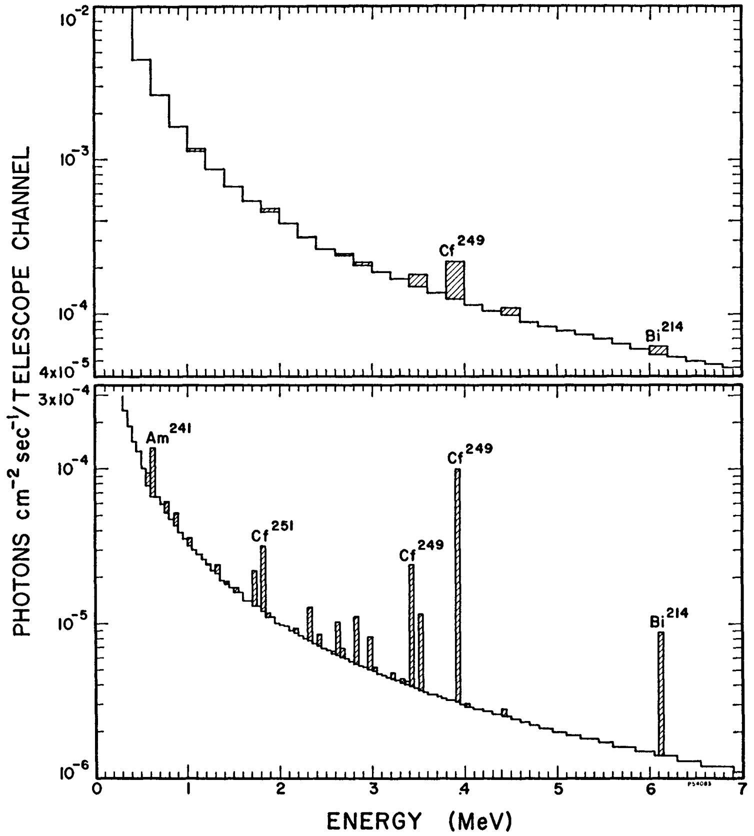

FIG. 2.—Line spectrum of Fig. 1 as it would appear atop the continuous extra-terrestrial photon flux observed by Arnold *et al.* (1962) when viewed with two idealized gamma-ray telescopes having the following properties: (*top*) channel width of 20 keV and solid angle of 0 1 srad; (*bottom*) channel width of 5 keV and solid angle of 0 01 srad.

find 0.6 K-X-rays/fission, consisting of broad maxima at about 19 keV and 32 keV corresponding to atomic numbers 43 and 55, which are believed to result from the internal conversion of prompt fission gamma rays. Apparently these X-rays form an insignificant fraction of the total numbers of prompt and delayed gamma rays, but they may be a significant feature in their restricted energy range. In summary, it appears that each spontaneous fission is accompanied by about sixteen gamma rays having a total energy of about 16 MeV. This large yield makes fission a potentially important source of gamma rays. The only nucleus that is expected to have significant fission activity 910 years after an *r*-process event is Cm^{250}. The 7.6×10^{38} decays per second of Cm^{250} anticipated by Table 2 produce a flux at the Earth of 8.1×10^{-5} fission gammas cm^{-2} sec^{-1} from the Crab Nebula. This flux is apparently not detectable since it is described by a continuous spectrum with magnitude much smaller than the sky background observed by Arnold *et al.* (1962).

The kinetic energy released in spontaneous fission may be a significant factor in the energy balance of the Crab, however. About 200 MeV of kinetic energy will be liberated by each Cm^{250} fission, of which about 90–95 per cent will remain with the heavy fission fragments themselves. The remainder will appear as six delayed beta-decays of the fragments and about three beta-decays of prompt neutrons. With 7.6×10^{38} decays per second, Cm^{250} fission contributes 2.5×10^{35} ergs/sec of kinetic energy to the nebula. We should also reiterate our *assumption* that there exist no beta-stable nuclei with masses in the range $260 < A < 275$ having fission half-lives as long as 100 years. If such nuclei do exist, they provide another source of fission energy in the Crab Nebula. We also feel compelled to observe that an *r*-process remnant will have an intense source of fission gamma rays shortly after the explosion. A continuous but rapidly decaying spectrum of the form found by Smith *et al.* should be one of the characteristic features of an *r*-process event unless the nebula is initially opaque to gamma rays with energies of hundreds of keV.

V. DECAY CHAIN ENERGETICS

Another potential source of energy to be considered in the energy balance of the Crab Nebula today is that released by the alpha-beta-gamma chains of transbismuth nuclei. The anticipated gamma line spectrum has already been discussed, but considerably larger amounts of energy appear as kinetic energy of alpha- and beta-particles. Table 4 lists the rate of energy liberation of the important radioactive nuclei 910 years after the *r*-process event. Separate columns give the alpha-particle energy rates, the beta- (plus neutrino) energy rates, and the gamma-energy rates. The branching ratios in the alpha- and beta-decays were taken from Landolt-Börnstein compilation. Several had to be estimated by us, but any associated errors in the rate of energy release will be small. Since it is impractical to list all radioactive species, we have arbitrarily decided to include in Table 4 only those species presently making more than 10^{38} decays/sec in the Crab Nebula (if the assumed production-curve R_A is correct). As justification we note that the species listed are responsible for 99 + per cent of the energy generation. (The largest unlisted contributor is the spontaneous fission branch, 11 per cent, of Cm^{248}, which would liberate 2×10^{33} ergs/sec.) The total rates of radioactive energy release in these three modes are given at the conclusion of Table 4.

From the sums in Table 4, it is apparent that radioactive energy release will be an important consideration in the energy balance of the Crab Nebula if the Cf^{254}-hypothesis is correct. Inclusion of the 2.5×10^{35} ergs/sec from the Cm^{250} fission brings the radioactive luminosity to 1.16×10^{36} ergs/sec, of which 94 per cent lies in the kinetic energy of heavy ions (5–6-MeV alpha-particles and 60–140-MeV fission fragments). This power input is two orders of magnitude greater than the radio luminosity, approximately equal to the X-ray luminosity, and within an order of magnitude of the optical luminosity. The qualitative effect of the kinetic energy release will be to provide internal pressure and turbulence in the portion of the plasma containing the radioactive debris. That "live" plasma may, in its interaction with the dormant plasma environment, concentrate a significant fraction of its energy into electrons by a not-yet-understood acceleration mechanism. (The interaction of the solar wind with the Earth's magnetosphere is providing a modern laboratory for the study of this mechanism.) The immediate point is that, because the radioactive energy release is so large, a thorough understanding of the Crab remnant is impossible without knowing whether to include the radioactive energy source. A search for nuclear gamma rays appears to be the only way of deciding this question.

In view of the large radioactive energy output possible in the Crab Nebula, we have also calculated the radioactive heating of an average galaxy. To do so we again assumed the Cf-hypothesis to be correct and that Type I supernovae occur at the rate $(300\ \text{yr})^{-1}$/galaxy. We considered the energy release only from species having half-lives in excess of 100 yr in order to separate the energy released in interstellar gas from energy released

TABLE 4

DECAY CHAIN ENERGETICS

Nucleus	dN/dt (sec^{-1})	K E (α) (ergs/sec)	K E ($\beta\nu$) (ergs/sec)	E (γ) (ergs/sec)
Cf^{251}	$2\ 4\times10^{40}$	$2\ 4\times10^{35}$		$1\ 0\times10^{33}$
Cf^{249}	$1\ 8\times10^{40}$	$1\ 7\times10^{35}$		$9\ 9\times10^{33}$
Cm^{246}	$1\ 8\times10^{39}$	$1\ 6\times10^{34}$		...
Cm^{245}	$8\ 0\times10^{39}$	$6\ 9\times10^{34}$		$4\ 0\times10^{32}$
Am^{243}	$2\ 2\times10^{39}$	$1\ 9\times10^{34}$	...	$2\ 3\times10^{32}$
Pu^{241}	$8\ 0\times10^{39}$	...	$2\ 6\times10^{32}$	...
Am^{241}	$1\ 9\times10^{40}$	$1\ 7\times10^{35}$	...	4.5×10^{33}
Pu^{240}	$1\ 7\times10^{39}$	$1\ 4\times10^{34}$	...	3.0×10^{31}
Np^{239}	$2\ 2\times10^{39}$	...	$1\ 2\times10^{33}$	$1\ 2\times10^{33}$
Pu^{239}	$1\ 3\times10^{39}$	$1\ 1\times10^{34}$		$7\ 0\times10^{31}$
Pa^{231}	$4\ 3\times10^{38}$	$3\ 5\times10^{33}$		$2\ 7\times10^{31}$
Th^{230}	$1\ 8\times10^{38}$	$1\ 4\times10^{33}$		$5\ 2\times10^{30}$
Th^{229}	$4\ 6\times10^{38}$	$3\ 7\times10^{33}$	...	$9\ 2\times10^{31}$
Ac^{227}	$4\ 3\times10^{38}$	$4\ 2\times10^{31}$	$2\ 5\times10^{31}$	$4\ 0\times10^{30}$
Th^{227}	$4\ 2\times10^{38}$	$4\ 1\times10^{33}$	...	$1\ 5\times10^{32}$
Ra^{226}	$2\ 1\times10^{39}$	$1\ 7\times10^{34}$	...	$1\ 9\times10^{32}$
Ra^{225}	$4\ 6\times10^{38}$	...	$2\ 4\times10^{32}$	$1\ 9\times10^{31}$
Ac^{225}	$4\ 6\times10^{38}$	$4\ 3\times10^{33}$		$1\ 1\times10^{32}$
Ra^{223}	$4\ 3\times10^{38}$	$3\ 9\times10^{33}$		$1\ 9\times10^{32}$
Rn^{222}	$2\ 2\times10^{39}$	$2\ 0\times10^{34}$		...
Fr^{221}	$4\ 9\times10^{38}$	$5\ 0\times10^{33}$		$2\ 9\times10^{31}$
Rn^{219}	$4\ 3\times10^{38}$	$4\ 8\times10^{35}$		$3\ 6\times10^{31}$
Po^{218}	$2\ 2\times10^{39}$	$2\ 2\times10^{34}$		
At^{217}	$4\ 2\times10^{38}$	$4\ 8\times10^{33}$		
Po^{215}	$4\ 3\times10^{38}$	$4\ 9\times10^{33}$	...	...
Pb^{214}	$2\ 2\times10^{39}$	...	$2\ 6\times10^{33}$	$1\ 1\times10^{33}$
Bi^{214}	$2\ 2\times10^{39}$	...	$5\ 4\times10^{33}$	$5\ 9\times10^{33}$
Po^{214}	$2\ 2\times10^{39}$	$2\ 6\times10^{34}$	...	...
Bi^{213}	$4\ 6\times10^{38}$	$8\ 8\times10^{31}$	$9\ 2\times10^{32}$	$1\ 1\times10^{33}$
Po^{213}	$4\ 6\times10^{38}$	$6\ 1\times10^{33}$	...	...
Pb^{211}	$4\ 3\times10^{38}$	...	$8\ 4\times10^{32}$	$1\ 1\times10^{32}$
Bi^{211}	$4\ 3\times10^{38}$	$4\ 6\times10^{33}$	...	$3\ 6\times10^{31}$
Pb^{210}	$2\ 2\times10^{39}$	...	$7\ 7\times10^{31}$	$1\ 4\times10^{32}$
Bi^{210}	$2\ 2\times10^{39}$	...	$4\ 1\times10^{33}$	
Po^{210}	$2\ 2\times10^{39}$	$1\ 9\times10^{34}$	...	
Pb^{209}	$4\ 6\times10^{38}$	...	$4\ 7\times10^{32}$	
Tl^{207}	$4\ 3\times10^{38}$	...	$9\ 1\times10^{32}$	
Total ..	...	$8\ 7\times10^{35}$	$1\ 7\times10^{34}$	$2\ 7\times10^{34}$

during the explosion. The calculation is quite simple in that each radioactive species builds up to its equilibrium abundance in interstellar gas. The resultant power output per galaxy is 1.4×10^{38} ergs/sec, of which about 94 per cent will be in the form of kinetic energy of heavy ions. Although this result is small compared to the optical luminosity of galaxies, it is comparable to the radio luminosities of most galaxies and could be relevant to some feature of gas dynamics. The radioactive chain originating with Th^{229} accounts for 36 per cent of the energy and the fission of Cm^{250} accounts for 18 per cent. The gamma-ray luminosity of such a galaxy due to radioactivity is 5×10^{36} erg/sec. This luminosity is probably much smaller than that due to other gamma-ray sources, even over the range 100–500 keV in which most of the line gammas occur. Certainly the counting rate observed by Arnold *et al.* on Ranger 3 is about two orders of magnitude greater than the flux anticipated from such radioactivity in our own Galaxy.

VI. CONCLUSION

We have examined quantitative implications of the Cf-hypothesis. Without knowledge of its correctness, it is impossible to unambiguously interpret (1) the Type I light-curves, (2) the source of *r*-process nucleosynthesis and its implications on galactic evolution, and (3) the present-day energy balance in supernova remnants. We have calculated the radioactive energy release for the Crab Nebula (assuming correctness of Cf-hypothesis) to facilitate its possible applications to other phenomena. The chain of possibilities is so involved that there seems little hope to unravel the true situation without a direct observation of the phenomenon involved. We have presented the anticipated gamma-ray spectrum of the residual radioactivity and roughly assessed the requirements of a telescope capable of detecting it.

Dr. R. C. Haymes has stimulated this calculation by undertaking the observation of gamma rays from the Crab Nebula. We are grateful to Dr. S. A. Reynolds of ORNL for providing several gamma-ray branching ratios for our use. This work was supported in part by AFOSR Grant No. 855-65.

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