COSMIC RAYS FROM SUPERNOVAE AND COMMENTS ON THE VELA X PRE-SUPERNOVA

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The discussion of the Gum Nebula which has taken place at this conference has relied to a great extent upon postulates about the character of supernova explosions and of the ionizing particles which can be ejected from them. I will first discuss the average properties of supernova explosions which were found in a recent study of chemical evolution of the galaxy, carried out by J. W. Truran and myself, and then make some remarks on the Vela X supernova.

In this study we have been playing a kind of game in which we try to account for the history of the production of elements in the galaxy by making a fairly large number of assumptions about the end points of stellar evolution and of the general evolution of the galaxy. We try to fit a wide range of observable quantities involving the relative abundances of the different products of nucleosynthesis observed in the solar system, and various galactic quantities such as the current rate of supernova production and the present gas content of the galaxy. The game consists of making these assumptions about the production of different products of nucleosynthesis at the end of stellar evolution, and utilizing them in a computer program in which the gas content of the galaxy is gradually turned into stars, being continually enriched in the products of nucleosynthesis as the stars which are formed come to the ends of their evolutionary lifetimes. We assume that the gas content of the galaxy decreases exponentially with time, to become only 5 percent of the galactic mass at the present age of the galaxy, which we find to be 12 billion years. Except for the first generation of stars, which we take to be all massive, we assume the stellar birth function which was first put together by Salpeter and by Limber. The computer code keeps track of the numbers of stars which are formed at different galactic evolutionary times, and mixes back the nucleosynthesis products from these stars into the interstellar medium when the stars come to the end of their evolutionary lifetimes. The mixing is assumed to take place instantaneously in the interstellar medium. The galaxy is taken to be structureless and featureless, since we are interested in the effects which occur when mass is cycled repeatedly between stars and the interstellar medium.

In addition to obtaining the right relative proportions of the products of nucleosynthesis at the time of formation of the solar system, which we find to be 7.4 billion years, we also wish to obtain consistency among the ratios of the radioactivities which are produced during nucleosynthesis, and which were incorporated into the solar system at the time of its birth. These radioactivities include thorium 232, uranium 235 and 238, and the extinct radioactivities plutonium 244 and iodine 129. We also wish to obtain a supernova rate in the galaxy at the present time of about one event per 25 years, to be consistent with the rate found by Tammann in a study of spiral galaxies similar to our own.

Time does not permit a lengthy exposition of the features of the model of galactic nucleosynthesis which we have studied. The aspects of this study which are most relevant to the present discussion concern the parameters which we found necessary to assign to supernova explosions in order to account for the abundances of the different products of nucleosynthesis in the solar system.

Figure 1 shows the assumptions which we had to make about the end points of stellar evolution in order to obtain a consistent picture of the chemical evolution of the galaxy. I shall discuss only the aspects of the supernova explosions shown in this figure. However, it should first be remarked that in the smaller mass range, where white dwarfs are found, Paczynski has found that the mass loss rates in the formation of planetary nebulae become sufficiently great so that the Chandrasekhar limit on the degenerate core is not reached until a main sequence mass of about 3.5 or 4 solar masses. Beyond this point, the degenerate core in the late state of stellar evolution would exceed the Chandrasekhar limit, and therefore something more catastrophic than the formation of a white dwarf remnant should occur.

An estimate was made by Gunn and Ostriker of the mass range of the stars needed to form the observed number of pulsars. They found that this mass range should lie about from 3.5 to 8 solar masses, which is consistent with our assumed range of 4 to 8 solar masses. Barkat has recently shown, as mentioned by Colgate, that there is a range of mass, from 4 to 8 solar masses, where the cores of stars in advanced stages of evolution evolve in essentially the same way.

These independent approaches all suggest that supernova explosions are to be associated with the mass range of about 4 to 8 solar masses.

The lower limit of 4 solar masses cannot be changed very much without changing significantly the number of supernovae which should currently be observed in the galaxy. The lower limit which we have chosen gives one supernova per 25 years, although this rate is specifically linked to the assumptions about the stellar birth function, which falls off rapidly toward higher masses, and to the assumed rate of depletion of the interstellar gas in the formation of stars. However, even if these quantities were to be significantly modified, the lower limit of 4 solar masses could not be changed very much. On the other hand, the upper limit of the assumed supernova range is very much more uncertain.

Note that in Fig. 1 the combined masses of the assumed neutron star remnant and the layer in which the range of elements from carbon to iron is formed by explosive nucleosynthesis account for 28 percent of the stellar mass. This is about the fraction of the star which can be expected to lie in the stellar core following helium burning. We find that we require 8 percent of the stellar mass to give the products of explosive nucleosynthesis which lie in the range carbon-to-iron. Consequently, it is strongly indicated on the basis of our overall mass balance that a reimplosion must occur during the supernova explosion in order to form the neutron star. If the entire core were to be exploded, giving the products of explosive nucleosynthesis, then we would have to restrict the range of stellar masses involved in supernova explosions to be a very narrow strip in this diagram, and that would seem to be physically unreasonable.

A fantastically small amount of material must be ejected in the average event to give the r-process elements. Only 10^{-6} of the stellar mass, or of the order of 5×10^{-6} solar masses can be ejected in the form of heavy neutron-rich elements. This is much less than the amount of mass which is ejected in the axial jets in the model of two-dimensional supernova explosions investigated by LeBlanc and Wilson. This raises some interesting questions about the r-process, but these lie beyond the scope of this talk.

Beyond the region of explosive nucleosynthesis, there is a helium layer, assumed to be 5 percent of the mass, and then some sort of outer layer of hydrogen which has never been subjected to nuclear burning. We have assumed that the star has lost mass in the red giant phase of its evolution, amounting to of order 35 percent of the main sequence mass. However, in the remaining hydrogen outer layer of the star, the supernova shock wave will be required to convert heavy elements into the p-process products, in which protons are added on to the heavy elements which have been formed by the s- and r-processes in previous generations of stars and stored in this outer hydrogen envelope since the time of formation of the star undergoing supernova explosion.

We have found that mass balance in the chemical evolution of the galaxy requires the processing of half the original content of the heavy elements in the outer hydrogen layer shown in Fig. 1. In order to produce the p-process elements, the supernova shock wave must heat the outer hydrogen layer to around 3×10^{9} °K in the region near the base of the hydrogen layer where the density will be of the general order of 1 gram per cubic centimeter or perhaps higher. Since much of the mass in the outer hydrogen layer will certainly be at much lower densities than this, it seems unlikely that the total content of heavy elements in this hydrogen layer can be converted to p-process products, and hence we feel that our assumed processing of half of the mass of these elements into p-process products is quite reasonable. In any case, there is a minimum requirement that about half to one solar mass of material should take place in the p-process in the average supernova explosion.

The type of stellar explosive event which emerges from this picture is obviously the type II supernova, in which hydrogen lines are observed in the spectrum. This approach, based upon accounting for the processes of nucleosynthesis, has not produced an explosive event which can easily be identified with the type I supernova.

Mrs. Charlotte Gordon, in an extensive study soon to be published, has interpreted the spectra of type I supernovae to represent the expansion of a supernova envelope in which hydrogen is quantitatively missing. She has identified a large number of emission features in the spectrum as involving forbidden coronal emission lines of a variety of elements, initially formed at kinetic temperatures near 10^6 °K in the inner layer of the expanding supernova shell. Later on, less highly-ionized elements produce lines when the temperature falls to around 10^5 °K.

Evidently our nucleosynthesis-based approach has missed the type of supernova explosion which would be represented by the type I spectrum. Since type I supernovae often occur in elliptical galaxies where there is currently very little formation of stars, it appears that such supernovae should arise from stars with masses not very different from that of the sun. J. W. Truran and I therefore make a suggestion for the origin of type I supernovae which may be consistent with the above constraints. If the Vela X supernova remnant is to be identified with the nearby young association of stars, then it is evident that it cannot have produced a type I supernova explosion, and hence our suggestions for the type I explosion will be given only briefly.

Consider a pair of binary stars with masses initially approximately equal to that of the sun. One of them, slightly more massive than the other, will evolve off the main sequence first, and will then transfer most of its mass to the other, leaving behind a helium white dwarf which is not very massive. When the second star evolves, at a later date, there will be a reverse transfer of mass. Presumably this will result in a series of nova explosions occurring as mass addition occurs on the white dwarf star, accompanied by a great deal of hydrogen burning near the surface, which gradually builds up a helium white dwarf toward the Chandrasekhar limit. When this occurs, ignition of helium thermonuclear reactions will occur, leading to a thermonuclear explosion which will blow the star apart. One of my students, Mr. T. Mazurek, is currently carrying out supernova hydrodynamic calculations to investigate this process. This type of explosion, in which the thermonuclear ignition occurs at densities near 10^{10} grams per cubic centimeter, should result in a reimplosion of the interior to form a neutron star, and hence a pulsar. It will also contribute somewhat to the abundance of the products of explosive nucleosynthesis in the galaxy.

Table 1 shows the mass fractions which are involved in our adjusted assumptions about the end points of stellar evolution.

Table 1
Compositional Structure at End of Life
(by mass fraction)

Mass Range	Description	Conventional Model	Consistent Model: First Generation	Consistent Model: Subsequent Generations
$M > 8\ M_\odot$	Black Hole Remnant	0.65	0.95	0.65
	Mass Loss	0.35	0.05	0.35
$4 \leq M \leq 8\ M_\odot$	Neutron Star Remnant	0.20	0.20	0.20
	r-Process Synthesis	1.3×10^{-6}	1.4×10^{-6}	1.4×10^{-6}
	Carbon-to-Iron Synthesis	0.075	0.08	0.08
	Helium Shell	0.05	0.05	0.05
	Hydrogen Envelope*	0.325	0.32	0.32
	Mass Loss	0.35	0.35	0.35
$M < 4\ M_\odot$	White Dwarf Remnant	0.50 (1.12 $M_\odot$ maximum)		0.50 (1.12 $M_\odot$ maximum)
	Helium Shell*	0.05		0.05
	Mass Loss	(Remainder)		(Remainder)

*Site of p-Process Synthesis: 50% of the primordial r-process and s-process nuclei are converted to p-process nuclei.

**Site of s-Process and Nitrogen Synthesis:

(a) all initial CNO-nuclei converted to nitrogen in masses $1 \leq M \leq 2\ M_\odot$;

(b) for stars of mass $2 \leq M \leq 4\ M_\odot$, 6.3% of the mass is converted to nitrogen and 0.375% of the C-Fe nuclei are s-processed (4.7% and 0.375%, respectively, for the Conventional Model).

Of particular concern here is that in a supernova range, 4 to 8 solar masses, only 8 percent of the region from carbon-to-iron is produced in the average event. The part of this which results in the formation of iron, which is expelled as nickel 56, is only 5 percent of this, which implies the ejection of only about 0.02 of solar masses of nickel 56 per average event. If much more than this is to be produced in the supernova which created the Vela X pulsar, then it would be necessary to conclude that the Vela supernova differed radically from the average event, ejecting an order of magnitude or more of nickel 56 than the average event.

Figure 2 shows the galactic history of nucleosynthesis which results from our assumptions. The figure shows the abundances, relative to those in the solar system, of various processes of nucleosynthesis in the interstellar medium as a function of galactic age. The various lines should go through unity at some galactic age which can be identified with the formation of the solar system. We find this to occur at 7.4 billion years, at which time we also have consistency from the cosmochronology. This gives the present age of the galaxy at 12 billion years. Note that the most abundant of the heavy elements are only moderately increased in abundance between the time of the formation of the solar system and the present epoch.

Thus the first major point I would like to make is that if the Vela supernova event resembled the average properties of the supernovae of type II which we find in this galactic history, then it could not have produced as much nickel 56 as Colgate would like to have in his theory of the supernova light curve, nor could it have produced the fluxes of heavily ionizing particles, consisting of ions such as nickel 56, which would be required in the theory of Colgate et al. to produce the ionization in the Gum Nebula.

The second major point that I would like to make is that we can use our model of galactic history to set limits on the amount of cosmic ray production by the average supernova explosion. These limits arise from the calculations of the production of lithium, beryllium, and boron by cosmic ray bombardment of the carbon, nitrogen, oxygen, and neon in the interstellar medium throughout past galactic history.

For this purpose we have taken the spallation production cross sections of the lithium, beryllium, and boron which have been estimated on the basis of experimental data by Henri Mitler at the Smithsonian Astrophysical Observatory. We have scaled the present interstellar cosmic ray flux back in time in proportion to the rate of supernova activity predicted in the model to exist in the galaxy as a function of past time. We have also adopted Mitler's values for the low-energy cosmic ray flux, demodulated from solar system values to the interstellar medium. We believe that at low energies his demodulation factor may have been somewhat too large, and that it may therefore predict too much production of the beryllium and boron. This demodulated cosmic ray spectrum is shown in Fig. 3. We have used the dashed line shown in this figure for the demodulated flux.

Figure 4 shows the calculated supernova activity rate throughout galactic history. The present rate is about one per 25 years. The rate in the early history of the galaxy is an order of magnitude greater than that. It is evident in Fig. 2 that the CNO-Ne abundances rise fairly rapidly in early galactic history, so that the main production of the lithium, beryllium, and boron in the interstellar medium will be concentrated in the early history of the galaxy.

Figure 5 shows our calculated abundances of the two isotopes of lithium, and of beryllium plus boron in the interstellar medium as a function of galactic age. In the case of the beryllium and boron, there are two assumptions that have been made, in one of which it is assumed that the beryllium and boron have been destroyed in the mass which is ejected from stars by stellar winds, and the alternative assumption is that the beryllium and boron survived in the lower temperature regions of the mass which is ejected from the stars by stellar winds. It may be seen that there is not a great deal of difference in the results of these tso assumptions.

The abundance of lithium 6 agrees reasonably well with the amount observed in the solar system. Beryllium and boron are too high by about a factor of 3. We believe that the discrepancy corresponds in part to the assumed demodulation of the cosmic ray spectrum, and in part to errors in the spallation production cross sections.

The cosmic ray spallation processes do not make enough lithium 7. The lithium 7 shown in Fig. 5 is made partly by cosmic ray spallation, and partly by another mechanism involving production in stellar interiors which has been suggested in a recent paper by W. A. Fowler and myself.

The basic point that I wish to make here is that the nucleosynthesis of the lithium, beryllium, and boron can be quite adequately explained by cosmic ray bombardment of the interstellar medium throughout past galactic history. The results are in quantitative agreement with the amounts found in solar system materials, subject to the uncertainties in cosmic ray fluxes and production cross sections which I have already discussed.

The reason for emphasizing this point is that one may suggest that ionizing particles ejected from the Vela supernova event may be responsible for the ionization produced in the Gum Nebula. In our picture we assume that the supernova explosions are responsible for the production of the present fluxes of cosmic rays in interstellar space. The average production rate of cosmic ray particles from supernova remnants can be estimated if one assumes an average age for the cosmic rays present in the galaxy. Such a production rate for the average supernova event seems inadequate to explain the ionization produced in the Gum Nebula. If one wishes to assume an additional flux of ionizing particles which would be needed to account for the ionization in the Gum Nebula, then these particles would have to be concentrated in the lower energy region, of less than about 10 MeV per nucleon, in order to avoid an excessive production of lithium, beryllium, and boron in the interstellar medium, which is already accounted for quantitatively by the demodulated flux shown in Fig. 3, or by a somewhat smaller flux at lower energies.

The net conclusions from this approach to the average supernova event are therefore that a medium energy flux of energetic protons and alpha particles seems unlikely to account for the ionization in the Gum Nebula. Also, it seems unlikely that enough heavier ions, such as nickel 56 and its decay products, can be ejected from the supernova event to account for the ionization of the H II clouds in the Gum Nebula region.

This seems to leave us with the requirement that about 10^{52} erg of ultraviolet radiation should be produced in order to account for the ionization in the Gum Nebula. The source of this ultraviolet radiation may very well be the pulsar formed in the supernova explosion, where the initial rotational energy may easily be of the order of magnitude of 10^{52} erg. The bulk of this energy is likely to be lost fairly early in the lifetime of the Vela X pulsar, in the first few years. Much of the energy may be emitted in x-rays from the pulsar region, which would be scattered from the expanding envelope once the density of the expanding nebulosity has become sufficiently low. In addition, if the slowing of the pulsar rotation occurs as a result of magnetic dipole radiation, which accelerates particles in the circumstellar region, then a great deal of the ultraviolet emission may be produced by the accelerated electrons releasing synchrotron radiation when they spiral in the surrounding system of magnetic fields. The detailed investigation of such ultraviolet emission mechanisms remains a task for the future.

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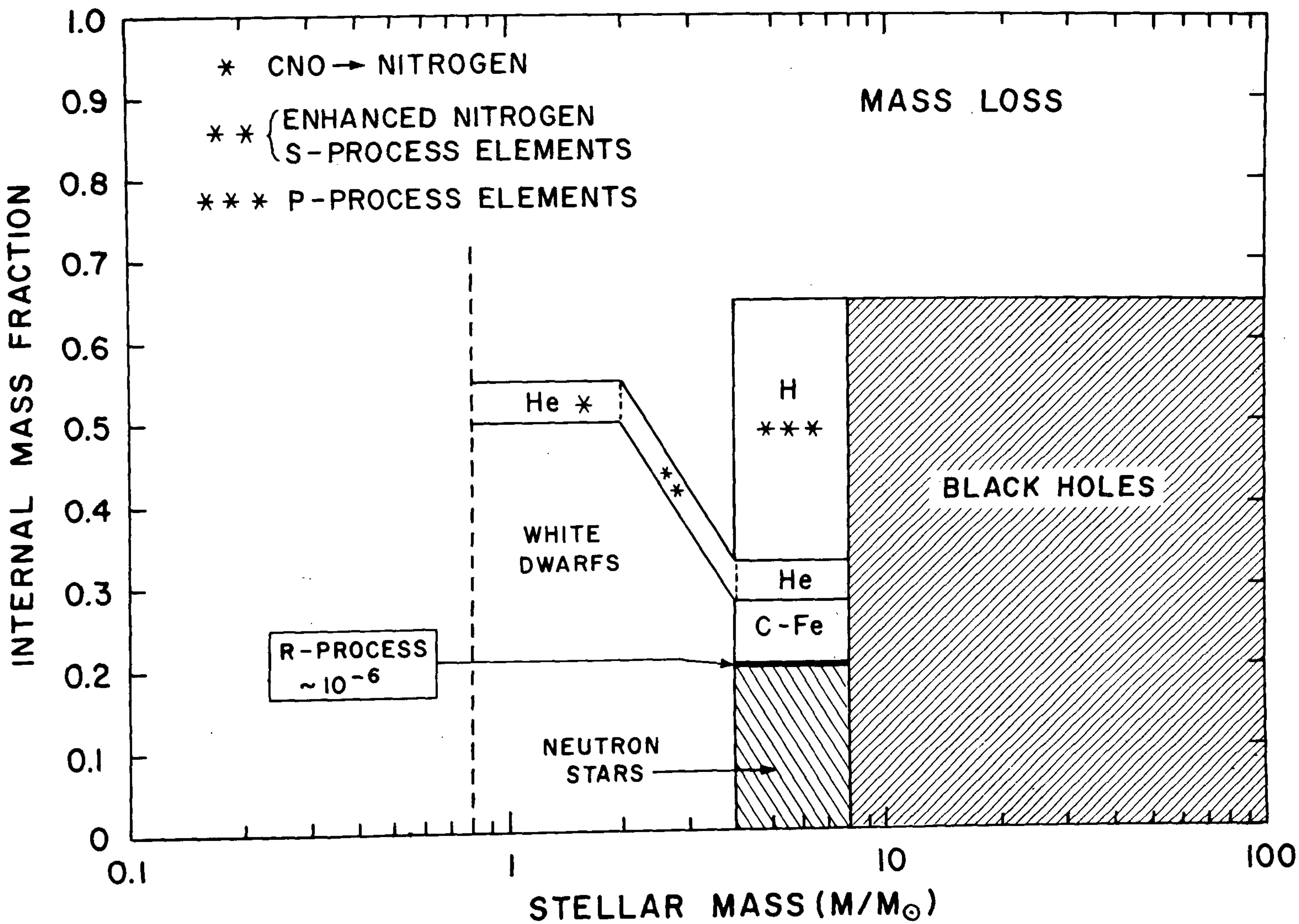

Figure 1. The adopted compositional structures for stars in their final stages of evolution. The fractional stellar masses, both in the appropriate remnant and in various nuclear burning zones, are indicated as a function of main sequence mass.

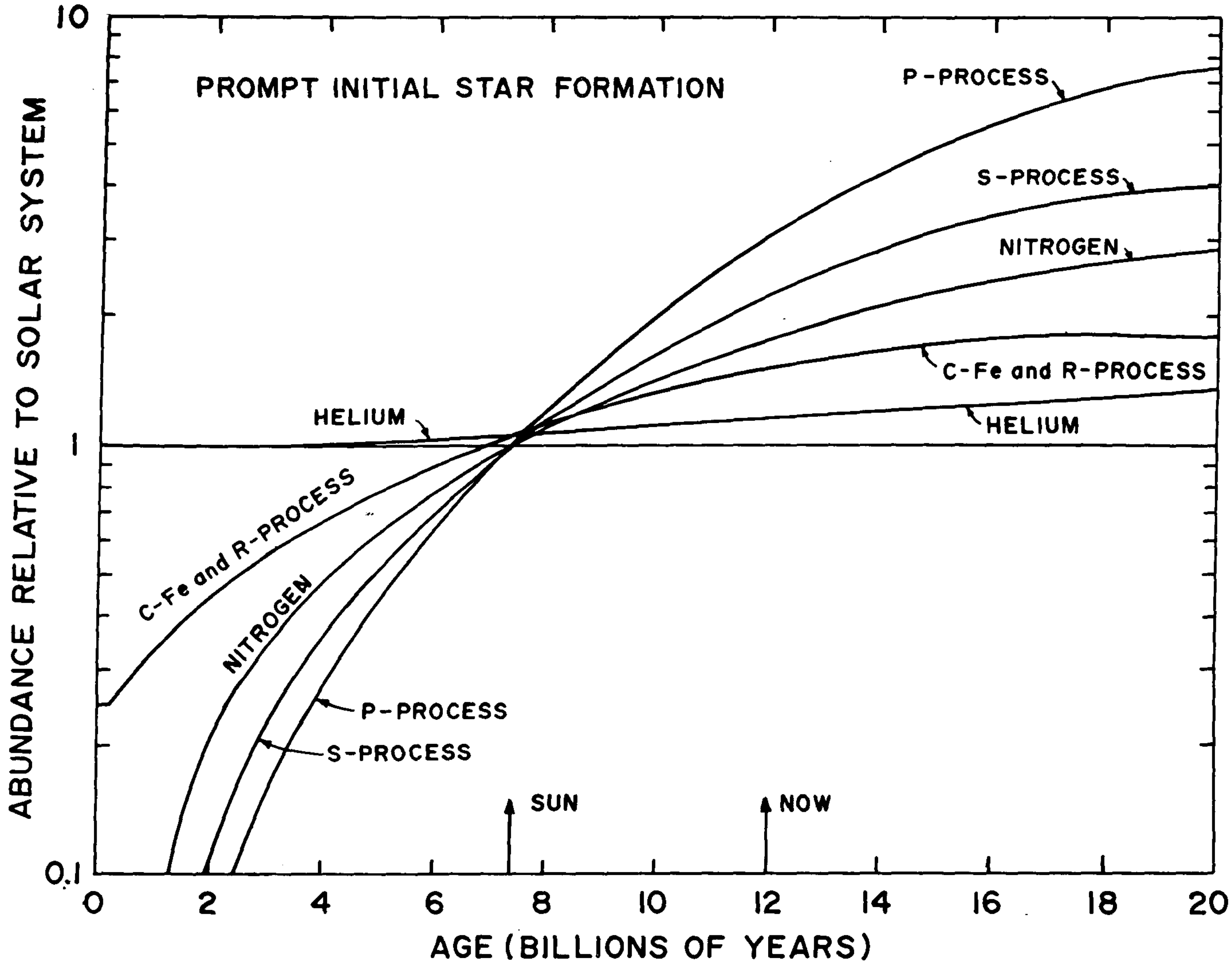

Figure 2. The abundances of nuclei formed by the various mechanisms of nucleosynthesis, relative to their solar system values, are shown as a function of galactic age for the adopted galactic model.

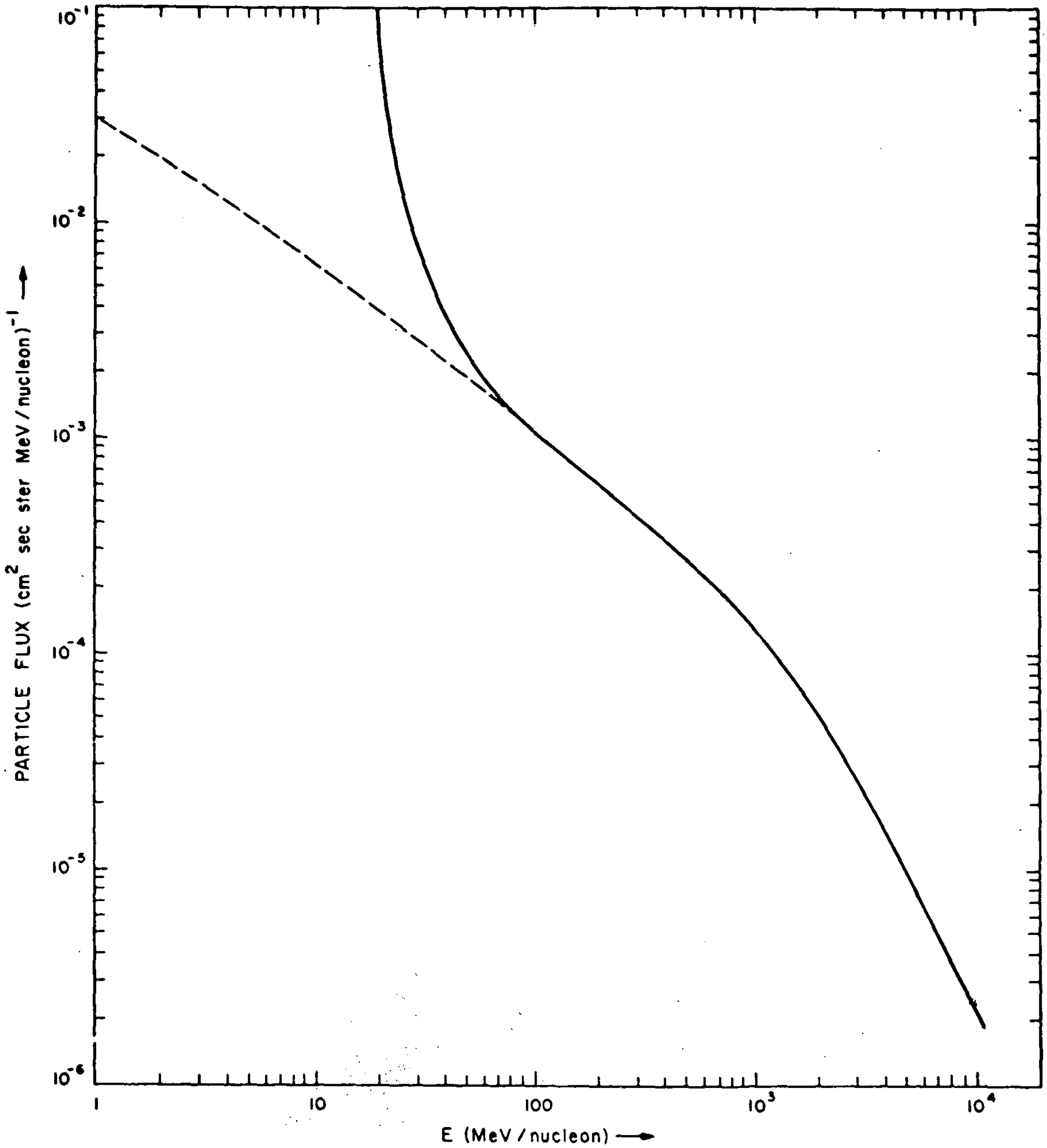

Figure 3. The observed $p + \alpha$ cosmic ray flux, demodulated with $\eta = 0.5$ GV and $R_0 = 0.4$ GV. The dashed line is an approximate extrapolation of the high-energy part of the curve, tangent at E = 100 MeV/nucleon.

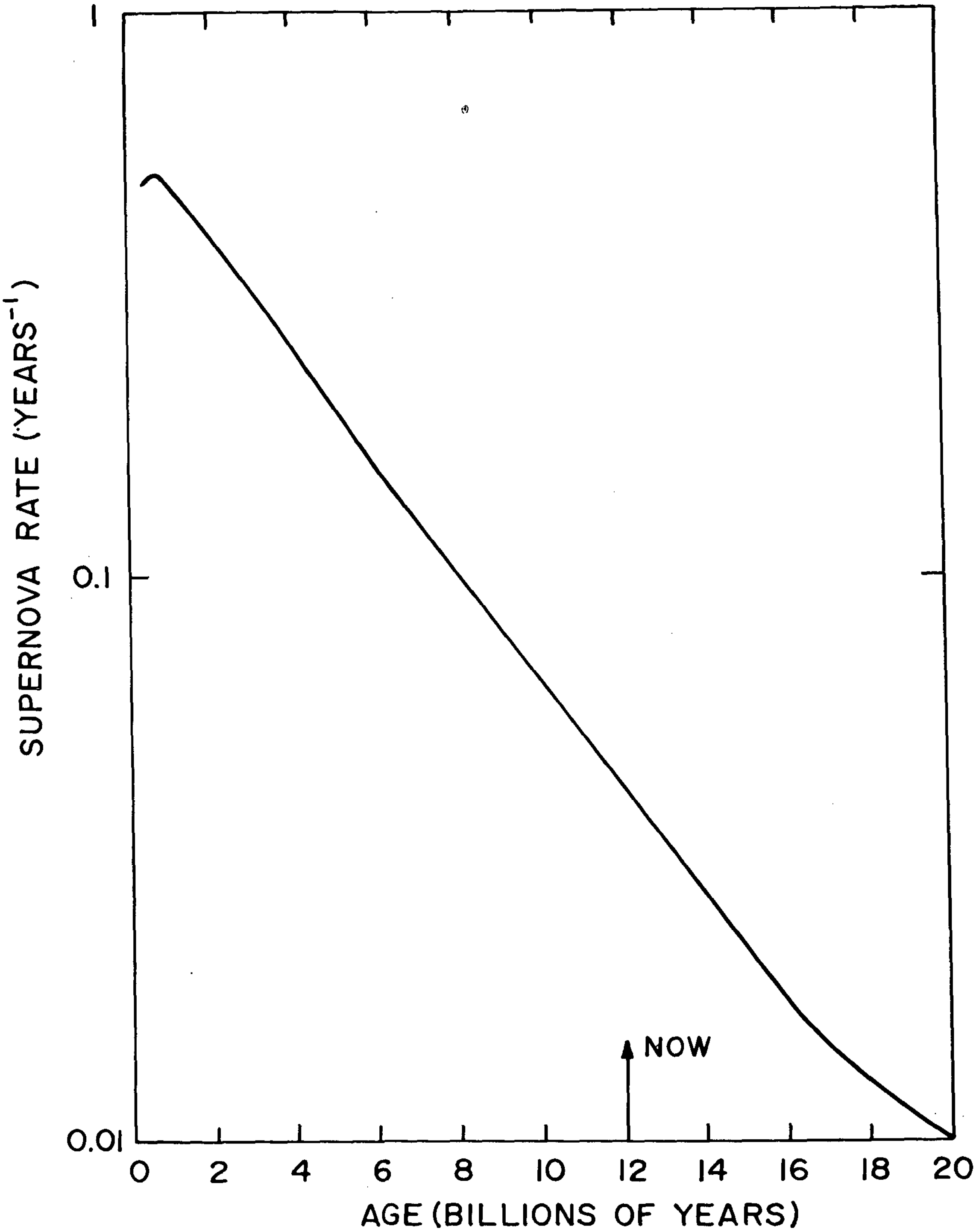

Figure 4. The rate of occurrence of supernovae (events per year) in the galaxy is plotted as a function of galactic age.

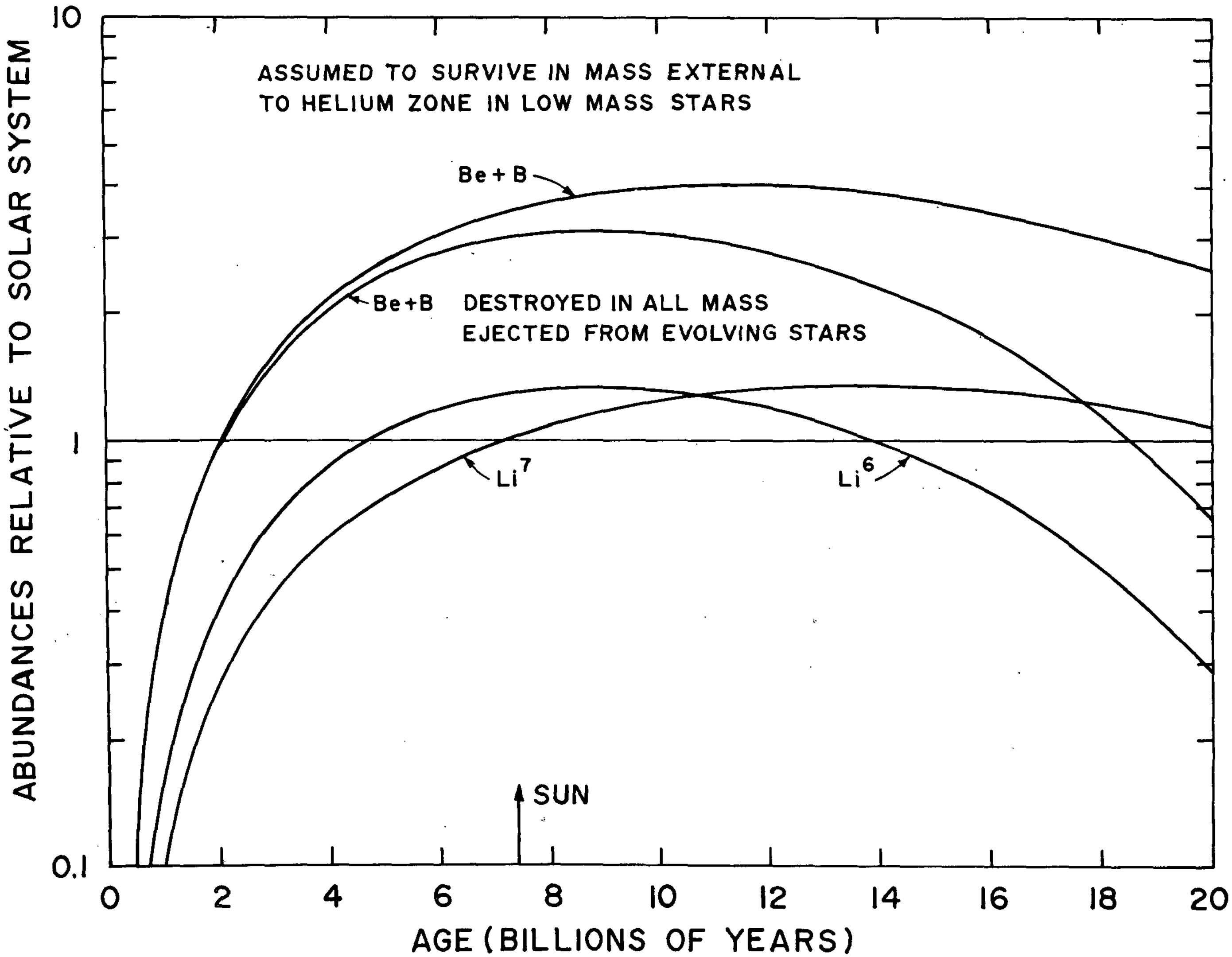

Figure 5. The abundances of Li^6, Li^7 and the isotopes of beryllium and boron in the interstellar medium, relative to solar system matter, are plotted as a function of galactic age. The two curves for Be + B correspond to limiting assumptions concerning their destruction in stellar envelopes.

DISCUSSION

A. B. Underhill: Why is the rate of supernova activity much greater in the early history of the universe?

A. G. W. Cameron: The gas content of the galaxy is assumed to decrease exponentially with time in our galactic history models. Since we assume that most of the supernovae arise from the mass range 4 to 8 solar masses, in which the evolution time is short, then the supernova rate becomes fairly accurately proportional to the star formation rate throughout past galactic history.

Question: Why does the abundance of lithium, beryllium, and boron decrease in the interstellar medium late in galactic history?

Cameron: The interstellar medium is enriched in the products of cosmic ray bombardment continually in time. However, since cosmic ray fluxes go down later in the history of the galaxy, the production rate becomes fairly small late in galactic history. The gas content of the galaxy also becomes quite small. Many stars were formed early in galactic history with a low content of lithium, beryllium, and boron, and this content may have been substantially destroyed in the stellar envelopes of these stars. When these stars reach the red giant phase, then mass ejection occurs by stellar winds, diluting the interstellar medium by gas with a lower content of the lithium, beryllium, and boron. This will cause an eventual downturn in the abundances of these elements.

F. W. Stecker: Do you assume that the helium was made primordially or as a result of stellar evolution?

Cameron: We assume that most of the helium was made by cosmological nucleosynthesis. Our specific assumption is that the initial content of helium in the galaxy was 23 percent, and by the time of formation of the solar system, only about another 2 percent of the mass had been converted to helium in the interstellar medium.

M. Shapiro: My recollection is that when Reeves et al. tried to make light elements by cosmic ray bombardment of the interstellar medium, they did not succeed too well. What is it that you did that changes this picture?

Cameron: Reeves, Fowler and Hoyle did succeed in principle in forming the lithium, beryllium, and boron in the interstellar medium by cosmic ray bombardment. We make somewhat more than their estimate because we allow for the higher rate of supernova activity and coxmic ray fluxes in past galactic history. However, we have not produced any qualitative change in the picture.

Question: Is this a promising method of getting the deuterium as well?

Cameron: No.

S. A. Colgate: If you integrate under the curve for the supernova rate times the time, you would find that the total number of supernovae is no more than two or three times the number you would get if you take the current rate and multiply it by the total age of the galaxy. Therefore, the total amount of iron produced in the supernovae should be no more than three times the current rate multiplied by the age of the galaxy. If you assume for the iron that 0.25 solar masses are produced in a supernova every 50 years, then this still gives you less mass of iron than is needed if you take something like 5 times the amount of iron that you would get in the solar composition, multiplying it by the mass of the galaxy. Can you comment on the discrepancy between your estimate of the needed production rate and mine?

Cameron: In our model, the average composition of iron in the total mass of the galaxy is somewhat less than that in the sun, so that we need only produce about 5×10^7 solar masses of iron, contrasted to your estimate of about 2×10^8, based upon the solar composition. We find that about 2 percent of a solar mass of iron is formed in the average supernova explosion. We have one supernova explosion every 25 years. In your estimates previously you have generally taken one supernova explosion every century, so that if that rate were to be correct, it would be necessary to produce 8 percent of a solar mass of iron per event. The remaining discrepancy between 0.08 solar masses and your estimate of 0.25 solar masses appears to lie in the fact that our detailed model shows that a total production of iron of only 5×10^7 solar masses is needed, which is less than the amount you have estimated.

F. W. Stecker: To what extent does your success in producing the lithium, beryllium, and boron in the galaxy depend upon fitting parameters, and how strongly do the lithium, beryllium, and boron abundances imply a high rate of supernova activity in the early history of the galaxy?

Cameron: We did not do any fitting in the calculations of the production of lithium, beryllium, and boron. All of the fitting which we did in producing the model had to do with the other main processes of nucleosynthesis, and we used the resulting model in a purely predictive sense to calculate the production of the lithium, beryllium, and boron. If anything, we make too much of these elements, but I am not concerned about this due to the various uncertainties which I have described. I do not think that this quantitative success demonstrated the validity of the precise curve which we have shown for the supernova activity in the early history of the galaxy, but I do believe it demonstrates the need for a higher average supernova rate throughout past galactic history than at the present time.

J. R. Gott: In connection with your diagram of the composition of the end points of stellar evolution, I have a concern about the runaway stars observed by Blaauw. There are about 20 of them that range in spectral class all the way out to about 07. This would seem to indicate that the companion stars which underwent a supernova explosion would have to be still more massive, and would have to lose the bulk of their mass in the explosion.

Cameron: Our assumed supernova range of 4 to 8 solar masses is not inconsistent with the existence of a lower mass stellar companion with a spectral class of early B or late O. In the explosion itself, we assume that 20 percent of the main sequence mass will remain behind as a remnant, and 45 percent of the main sequence mass will be ejected in the explosion. This does not seem to be inconsistent with the dynamics required to form runaway stars.