8-1-1974

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THE ASTROPHYSICAL JOURNAL, 191:705–710, 1974 August 1

NUCLEOSYNTHESIS IN WHITE-DWARF ATMOSPHERES

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Received 1974 January 28

ABSTRACT

We propose events by which both *s*- and *r*-process nucleosynthesis may occur on the surfaces of white-dwarf stars. The main requirement is that the accreted hydrogen be mixed with comparable numbers of ^{12}C (or other alpha nuclei) before a runaway capture of protons takes place. Subsequent events offer many possibilities for nucleosynthesis and stars of peculiar composition. A new mechanism for a surface *s*-process due to few-MeV protons is also described. Concluding comments concern cosmic γ-ray bursts and the origin of anomalous low-energy galactic cosmic rays.

Subject headings: cosmic rays — gamma ray bursts — nucleosynthesis — white-dwarf stars

I. INTRODUCTION

While many details of the production of heavy elements by the *r*- and *s*-processes are well understood from a nuclear point of view, the astrophysical circumstances under which these processes occur are less securely established. In this paper we discuss a new astrophysical model that appears to give a wide range of interesting possibilities. The model starts from the picture of the nova phenomenon recently discussed by Rose (1968), Rose and Smith (1972), Starrfield (1971*a*, *b*), Starrfield *et al.* (1972), and Starrfield, Sparks, and Truran (1973). Material of approximately solar composition is considered to be transferred in a binary system from a giant to a white-dwarf companion. In the most detailed calculations available the parameters assumed for the white dwarf by Starrfield *et al.* are: radius $R = 8 \times 10^8$ cm, mass $M = 1.00\ M_\odot$, rate of mass accretion approximately $10^{-8}\ M_\odot$ per year. By considering variations in the scenario we shift the emphasis from the nova phenomenon to the synthesis of heavy elements by neutron capture.

For the nova phenomenon itself the details of the chemical composition of the white dwarf are not important. One needs only that some nucleus capable of rapidly capturing protons at temperatures near $T = 2 \times 10^8$ °K be mixed with the infalling hydrogen gas. Starrfield *et al.* actually choose equal mass fractions of C and O for their white-dwarf models. The nova is achieved by increasing the capability for rapid nuclear energy by admixing more proton-capturing nuclei into the infalling matter. Peak nuclear powers near 10^{16} ergs g^{-1} s^{-1} are needed to eject matter; alternatively, energy of the order of 10^{17} ergs g^{-1} must be liberated in the few seconds required to saturate the proton captures. Starrfield *et al.* accomplished this by enriching the hydrogen envelope to about 30 percent C + O (by mass) due to mixing with the dwarf surface. For our purposes we will wish to consider other plausible possibilities for the dwarf surface composition and differing ratios of surface-envelope mixing.

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We expect the incoming accreted material to be capable of stirring the outermost regions of the white dwarf. Infalling material from a giant binary companion should reach the surface not in spherically symmetric radial infall but rather in a sequence of more or less randomly oriented disklike formations that form due to the nonzero angular momentum of successive streams. Consequently, accreted material will enter the dwarf surface in nearly horizontal streams. These would be capable of mixing the infalling material with the surface layer of the dwarf, thereby producing in the simplest case a mixture of hydrogen, helium, and carbon. Designating the number densities per unit mass by N_H, N_{He}, and N_C, we write

$$x = N_H/N_C\,, \qquad y = N_{He}/N_C\,. \tag{1}$$

Our aim is to study the nuclear evolution of the envelope in terms of the parameters x and y. The value of x will be determined by the extent to which the infalling hydrogen stirs and mixes the dwarf surface, whereas the value of y depends also upon whether He exists in the dwarf surface and upon the fraction of He in the infalling material.

Starrfield *et al.* consider the accreted material to have total mass $M \simeq 10^{-3}\ M_\odot$, and they regard it as being initially given in a cold state. Then because of the residual luminosity of the white dwarf the base of the accreted material gradually becomes heated. When the situation is eventually reached in which the nuclear power generated in the CNO cycle exceeds the radiative energy loss, a nuclear runaway takes place, with the temperature rising to about 2×10^8 °K. The runaway is not explosively disruptive to the envelope, however, because the rate at which the nuclear reactions can deliver energy is limited by the waiting time for β-decays. With $x \gg 1$, explosive conversion of hydrogen to helium requires many cycles in the chain $^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O(\beta^+\nu)^{14}N(p,\gamma)^{15}O(\beta^+\nu)^{15}N(p,\alpha)^{12}C$ and each such cycle takes several hundred seconds. This circumstance requires the adjustment of the envelope, although rapid, to be markedly subsonic.

Following the initial shock waves, the star develops a giantlike structure.

II. POSTSHOCK STRUCTURE

Although Starrfield *et al.* obtained their results from computer calculations, the extended structure taken up by the envelope can be understood in analytic form. Since this will be useful later, we give a brief discussion here. Pressure support comes largely from radiation pressure. Because the structural situation is not explosive, the envelope satisfies the hydrostatic approximation. In an obvious notation we have

$$\frac{1}{3}a\frac{dT^4}{dr} = -\frac{GM}{r^2}\rho\,. \tag{2}$$

Radiative transfer with opacity by electron scattering yields $\rho \propto T^3$, whereas convection with radiation pressure dominant requires $\rho \propto T^n$ with n only slightly less than 3. In a fair approximation we therefore put $\rho \propto T^3$ in equation (2). Writing ρ_0, T_0 for the density and temperature at the base of the envelope at $r = R$ gives an integral for equation (2):

$$T = \frac{3GM\rho_0}{4aT_0^{\,3}}\left(\frac{1}{r} - \frac{1}{R}\right) + T_0\,. \tag{3}$$

The much simpler form

$$T = T_0(R/r) \tag{4}$$

results from equation (3) when

$$\frac{3GM}{4R}\rho_0 = aT_0^{\,4}\,. \tag{5}$$

A condition close to condition (5) is in fact satisfied for any radiation-pressure–dominated envelope having radius r_s appreciably greater than R, so we will use it in estimating the envelope mass and T_0. With $\rho \propto T^3$ we than have

$$m = 4\pi\int_R^{r_s}\rho r^2 dr = 4\pi R^3\rho_0 \ln\frac{r_s}{R}\,. \tag{6}$$

Putting $m = 2 \times 10^{30}$ g, $R = 8 \times 10^8$ cm, and $\ln r_s/R \simeq 3$ gives $\rho_0 \simeq 10^2$ g cm^{-3}, and equation (5) leads immediately to

$$T_0 \simeq \frac{1}{R}\left[\frac{3GMm}{16\pi a \ln(r_s/R)}\right]^{1/4} \simeq 2 \times 10^8\,{}^\circ\mathrm{K}\,. \tag{7}$$

Although this structure is essentially in hydrostatic equilibrium, it is not unchanging. Even though an extended structure has been established, the nuclear power is still very large indeed and exceeds the luminosity losses. The star "solves" this problem by expanding further until r_s/R is a large number. Then the fact that the exponent n in the relation $\rho \propto T^n$ is somewhat less than 3 requires that the mass integral be more strictly expressed by

$$m = 4\pi\int_R^{r_s}\rho r^2 dr = \frac{4\pi}{3-n}\rho_0 R^3\left(\frac{r_s}{R}\right)^{3-n}\,. \tag{8}$$

Thus when r_s/R becomes large, ρ_0 becomes smaller for given m than the value derived from equation (6), and T_0 from condition (5) becomes correspondingly smaller. The structural problem is therefore "solved" by lifting most of the envelope material to a great distance from the white dwarf, a solution that demands a nuclear energy release of the order of $GM/R \simeq 1.6 \times 10^{17}$ ergs g^{-1}. The forcing of material to the outside continues until T_0 is reduced sufficiently for the nuclear power to fall to the normal radiative loss, given by the well-known formula (Eddington 1926)

$$L = 4\pi cGM(1-\beta)/\kappa\,, \tag{9}$$

where κ is the opacity. For electron scattering opacity, equation (9) gives about 10^{38} ergs s^{-1} in the case $M = M_\odot$, $\beta < 1$. Starrfield *et al.* find long-time solutions approaching $r_s = 10^{12}$ cm, $T_s = 15{,}000°$ K, $L \simeq 1.5 \times 10^4 L_\odot$. By this point ρ_0 has fallen to about 1 g cm^{-3}, from which condition (5) gives $T_0 \simeq 65 \times 10^6$ ° K, the temperature of the hydrogen-burning shell. From this time onward the envelope will evolve on a nuclear-burning time scale if it is stable against pulsation (see Sastri and Simon 1973 for analysis of the pulsational stability of the preshock structure).

Although hydrogen-burning with $x \gg 1$ does not lead to a dynamically explosive ejection of the envelope, Starrfield *et al.* discovered that the energy released by delayed radioactivity, following expansion of the envelope, can lead to about 10 percent of the envelope being expelled to infinity at speeds in the range 1000–2000 km s^{-1}. This possibility is considered by those authors to provide an explanation of the origin of novae. Values of x of the order of 10^2, instead of the solar value of the order of 10^3, are needed to give adequate concentrations of delayed radioactivity, amounting to about 10^{16} ergs g^{-1} of expelled material. The above remarks on the mixing of helium and carbon from the white dwarf with the accreted material make it reasonable that the proportion of carbon in the mixed envelope should be considerably greater than it is in solar material. Indeed, our present purpose is to examine the effect of the carbon concentration being still larger than the value discussed by Starrfield *et al.* Specifically, we shall consider the parameter $x = N_H/N_C$ to be of the order of unity in the following work.

As temperatures rise above 10^8 ° K, the time scale for (p, γ) reactions becomes short. As the temperature, $T \simeq 2 \times 10^8$ ° K, required for an appreciable expansion of the envelope is approached, the reaction time scales for C, O fall to $\sim 10^{-1}$ s. Compared with the subsequent β-decays, which require 10^2–10^3 s, the energy yield from the (p, γ) reactions can be regarded as prompt. As $x = N_H/N_C$ decreases, the prompt yield rises from the values obtained in the models of Starrfield *et al.* to a maximum value of about 3.5×10^{17} ergs g^{-1} at $x = 2$. At this value of x we have two protons to each ^{12}C nucleus, just sufficient to convert each such nucleus to ^{14}O. Here and in the following we ignore protons that have been more slowly captured in raising the temperature to the prompt region, since the energy required to do so is but a small fraction of the total available.

The situation for $x = 1$ is less energetic, but still large. We now have one proton to each ^{12}C, sufficient to convert each nucleus to ^{13}N, with a prompt yield of about 10^{17} ergs g^{-1}. Little ^{14}O is produced in this case, because $^{13}N(p, \gamma)^{14}O$ does not occur as rapidly as $^{12}C(p, \gamma)^{13}N$, since the Coulomb barrier for nitrogen is larger than for carbon. For $1 < x < 2$, the ratio of ^{14}O to ^{13}N produced by the prompt reactions is expressed by $(x - 1)/(2 - x)$, which gives equality at $x = 1.5$. Subsequent β-decays change ^{13}N to ^{13}C and ^{14}O to ^{14}N.

For $1 \leqslant x \leqslant 4$ the prompt energy yield is comparable with, or greater than, the gravitational energy, $GM/R \simeq 1.6 \times 10^{17}$ ergs g^{-1}, on the 1.0 $M_\odot$ dwarf. If the development of the nuclear instability occurred at the base of the envelope simultaneously everywhere over the surface of the star, we would thus expect the whole envelope to be explosively detonated, and a portion of it—perhaps most of it—to be expelled entirely from the star. However, exact simultaneity of explosion over the whole surface of the star appears unlikely, since it is a characteristic of nuclear instabilities that slight initial variations of temperature lead to markedly different moments of instability. Hence we expect different spots on the interface between the white dwarf and its envelope to reach instability at very different times. Instead of a single large explosion we then have many smaller explosions. Material expanding violently from a particular instability point will become tamped by surrounding material, reducing the kinetic energy of the material and allowing it to be controlled by the gravitational field. These local thermonuclear runaways may be responsible for the dwarf-nova phenomenon. As more and more such individual small "bombs" explode, the star is likely to develop an extended halo from which material may eventually stream away into space. The escape of radiation from such a halo produces a stabilizing effect, permitting the star to retain much of its envelope, even though the total nuclear yield exceeds the gravitational energy.

The dynamical situation we have just described is reminiscent of the behavior of Wolf-Rayet stars. Indeed, the division of composition, after β-decays, into excess ^{13}C for $x \simeq 1$ and excess ^{14}N for $x \simeq 2$ is also suggestive of a connection with this class of star. There is the difficulty, however, that the masses of Wolf-Rayet stars appear to be considerably greater than $M_\odot$—i.e., than white-dwarf masses—so the connection, if it exists, must only be a family one. Although we hesitate to make precise identifications, the present considerations appear to have a relation to the properties of other classes of unusual stars, as we shall see below.

On the other hand, a thermonuclear runaway at one place in the envelope may explode adjacent material. The adiabatic compression may then lead to a kind of detonation wave propagating around the dwarf surface. If so, a natural time width would be imposed on the initial burst.

III. *s*-PROCESS

We turn now to the case in which the parameter $x = N_H/N_C$ is somewhat less than unity. The prompt energy yield from proton captures is about GM/R per unit mass, and is therefore sufficient to give an appreciable expansion of the envelope. From the discussion starting at equation (2) and going to equation (7) we see that the temperature at the base of the envelope must then be about 2×10^8 ° K. At this temperature the ^{13}C formed by $^{12}C(p, \gamma)^{13}N(\beta^+\nu)^{13}C$ itself begins to burn through $^{13}C(\alpha, n)^{16}O$. For a temperature of 2×10^8 ° K and a helium density of 10 g cm^{-3} the time scale for this reaction is 10^7 s (Davids 1968). An *s*-type process corresponding to this time scale now becomes established, the seed nuclei being provided by the small quantity of heavier elements present in the envelope. The nuclear power under this condition is $\epsilon \simeq 5 \times 10^{10}$ ergs g^{-1} s^{-1}, so that if it occurs over the inner 1 percent of the envelope the power will rather nearly equal the radiative losses and the adjustments should be slow.

The energy yield from the (α, n) reaction is in total about 4×10^{17} ergs g^{-1}. We therefore require a substantial fraction of ^{13}C to burn to give an energy production comparable to GM/R. The situation is now similar to the case studied by Starrfield *et al.* in the sense that ample energy is available to enable the star to adopt a giant structure, with most of the material of the envelope lifted to great distances from the white-dwarf core. Taking this to occur when the yield is GM/R per unit mass, i.e., with about one-third of the ^{13}C burned, we have an *s*-process situation with one neutron released per three nuclei of ^{13}C at the stage where a giant structure becomes established. Most of the neutrons are captured by $^{13}C(n, \gamma)^{14}C$. That cross-section has strong temperature dependence through a 142-keV resonance, having a value of 0.015 millibarns (mb) near $T_8 = 2.5$. A heavier nucleus with a (n, γ) capture cross-section σ will have captured

$$N_c \approx 0.3 \frac{\sigma(^ZA)}{\sigma(^{13}C)} \text{ neutrons} \qquad (10)$$

in such a situation—considerably more than ^{13}C in terms of neutrons per nucleus. Thus $\sigma \simeq 3$ mb at ^{28}Si, and also for nuclei of similar atomic weight, so that as many as 50 neutrons per nucleus could be acquired by silicon—more than sufficient to provide for the building of such elements as P, Cl, K. In the case of building by neutron addition from ^{56}Fe the cross-sections are about 10 mb, giving enough neutrons per iron for the production of all *s*-process elements.

In fact, the neutron supply will probably be limited by the number of proton captures that occurred slowly in heating the material to the point of rapid proton capture ($T > 10^8$ ° K). This is impossible to judge without a specific accretion model; but it is not unreasonable to assume that, when $x < 1$, perhaps 10 percent of the protons will be captured in reaching fast ignition. This will have happened slowly enough that several percent of the initial ^{12}C will actually become ^{14}N before the protons are exhausted. Because its neutron cross-section is also of the order of 1 mb, the ^{14}N will to a certain degree limit the capture of neutrons by seed nuclei, at least until the ^{14}N has been converted to ^{14}C, joining the ^{13}C which has also been converted to ^{14}C. A wide spectrum of possibilities exists for having *s*-process nuclei and ^{13}C and ^{14}C mixed to the surface of a hydrogen-exhausted object. We return later to this surface peculiarity of carbon, because it leads to a hitherto unrecognized possibility for the production of D and ^{3}He. It also suggests a comparison with V605 Aquilae, which resembled a hydrogen-deficient carbon star three years after an outburst (Bidelman 1973).

Two possibilities following the establishment of a giant structure now arise. The giant structure may persist on a time scale determined by equation (9), i.e., with a reduction of the temperature at the core-envelope interface to a value somewhat below 2×10^8 ° K, at which the energy yield from carbon-burning is adjusted to equal the rate of radiation loss, about 10^{38} ergs s^{-1}. Since the total yield from all ^{13}C in the envelope, $4 \times 10^{17} m$ ergs, is about 10^{48} ergs for an envelope mass $m \simeq 10^{-3} M_\odot$, it follows that the time scale determined by equation (9) is about 10^{10} s, not much different from that which has been assumed in previous studies of the *s*-process. With a complete burning of this ^{13}C, the number of neutrons made available per seed nucleus becomes ample for almost any nucleosynthesis need. There is considerable question what these stars would actually look like. They could resemble a peculiar B star, for example, but they seem to be too luminous to have any simple connection with Ap stars. Some 10^4–10^5 of them may exist within the Galaxy, however.

A second major possibility arises if the envelope becomes sufficiently extended to exceed the size of the binary, in which case the envelope will be rapidly dissipated by transfer to the other component of the binary and perhaps by streaming off into space. In this second case it will be the other component that will show evidence of the *s*-process activity discussed above. This plausible sequence offers so many observational possibilities that we will not even try to list them.

In either case, the process of ^{13}C-burning lasts for no longer than 10^{10} s. Thereafter, we expect the whole sequence of events to be repeated. The white-dwarf component will eventually cool off, and more material will gradually be added to it from the other component, the time scale for the white dwarf to grow a new envelope being long compared with 10^{10} s. Once again the envelope can start in a comparatively cold state, and once again a nuclear instability in the (p, γ) reactions can take place. The whole process is similar to that described above, except in one important detail. When the *s*-process stage is reached on the second occasion, seed nuclei of a different kind will be present, different from the ^{28}Si, ^{56}Fe discussed above. Thus in the second process of neutron addition we expect seed nuclei from the first *s*-process—for example, nuclei in the Sr, Zr peak. These will then be processed further. Nor need we be limited to only two *s*-process phases. There can be either a few such phases or many, involving complex mixtures of seed nuclei. The range of possibilities seems bewilderingly large. A second difference is that ^{16}O from ^{13}C$(\alpha, n)^{16}$O, rather than ^{12}C, could capture most of the rapid protons this time, leading if $x < 1$ to a ^{17}O$(\alpha, n)^{20}$Ne neutron source. The next time the ^{20}Ne could capture most of the protons, giving an abundant ^{22}Na source that should be easily detectable (Clayton and Hoyle 1974).

IV. *r*-PROCESS

Next, we ask if there could be circumstances in which ^{13}C, produced in the manner described above, is burned on a rapid time scale, say of the order of 1–10 s, thereby giving rise to the *r*-process. Such lifetimes for ^{13}C result in a free-neutron density 10^{19}–10^{20} cm^{-3}. The reaction ^{13}C$(\alpha, n)^{16}$O is very temperature sensitive, a value near 4×10^8 ° K being sufficient to give a rapid burning time scale. From formula (7) it is seen that such a temperature would be attained in a situation entirely similar to that given above if either m were larger, say $10^{-2} M_\odot$ instead of $10^{-3} M_\odot$, or if R were smaller, say 4×10^8 cm instead of 8×10^8 cm. The latter possibility could arise of the mass M of the white dwarf approached more closely to the Chandrasekhar limit. A nuclear instability would occur in this case, with much of ^{13}C being burned. The total energy yield would be about $4 \times 10^{17} m$ ergs, i.e., 10^{49} ergs for $m = 10^{-2} M_\odot$. With the envelope exploded violently in such a case, the phenomenon approaches the class of supernovae in its energy content and in the speed of the resulting outburst. With most of ^{13}C burned, the number of neutrons made available per seed nucleus, taking an average cross-section of 10 mb for the (n, γ) reactions, would be about 300, sufficient to drive the seed nuclei into the region of the heaviest elements.

Fascinating possibilities now suggest themselves for having stars enriched on their surfaces with *r*-process elements. The first has to do with the remnant of the explosion. If only a fraction of the mass is actually ejected, the remaining distended envelope will be hot and will remain so in part due to the large ensemble of radioactive half-lives within the envelope. The high-luminosity resettling phase may be about 10^3 years from the gravitational work, whereas the ^{14}C radioactivity could maintain A-star luminosities for about 10^4 years. The structure and appearance of such an atmosphere requires special calculation, but it is a candidate for the Ap stars. It is also a candidate for V605 Aquilae, which in 1918 was almost supernova-like (Bidelman 1971). A previous shell around V605 Aql was apparently ejected some thousands of years ago. A second possibility is that the neighbor in the binary will be heavily enriched in *r*-process nuclei and in ^{14}C. A third possibility follows the cooling of the remnant, which will now be a white dwarf with large *r*-process concentrations in its surface. When more hydrogen has been accreted, the hydrogen explosion can begin again, so the whole range of possibilities repeats with *r*-process enrichment. The *r*-process overabundances of factors 10^3–10^4 observed in the Ap star HR 465 by Cowley *et al.* (1973) may require some such special scenario. The difficulty is to end with an object that looks like an A star, either on the dwarf or its companion.

How much *r*- and *s*-process material can be produced in these ways? This question may be tentatively answered by taking the numbers of *s*-process events to be comparable with the number of novae, say 20 per year, and with the numbers of *r*-process events being perhaps an order of magnitude smaller, say 2 per year. If we take $m = 10^{-3}\ M_{\odot}$ for the envelope mass in the *s*-process case, and $m = 10^{-2}\ M_{\odot}$ in the *r*-process case, we get $2 \times 10^{-2}\ M_{\odot}\ \mathrm{yr}^{-1}$ for the rate of processing of material in both cases. Then taking the mass fraction of seed nuclei to be 0.1 percent, we have $2 \times 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$ for the rate of production of *r*- and *s*-process nuclei, giving a total of $2 \times 10^5\ M_{\odot}$ for a galactic time scale of 10^{10} years. On this tentative basis we therefore obtain a fraction of about 10^{-6} of the mass of the Galaxy in the form of *r*- and *s*-process nuclei. While this is an order of magnitude low for P, Cl, K, Cu, and Zn, and an order of magnitude high for the heavier elements, within the range of the uncertainties the estimates are satisfactory, suggesting that an appreciable fraction of the observed *r*- and *s*-process materials may be produced by nuclear instabilities at the surfaces of white-dwarf stars.

V. SURFACE *S*-PROCESS, D, ^{3}He

Finally, we wish to point out a possibility for weak *s*-processes and for the synthesis of D and ^{3}He on the surfaces of stars. Consider a scenario that, because $x \simeq 1$, has produced a surface dominated either by ^{13}C from proton captures or by ^{14}C from subsequent neutron capture. The explosions of the white-dwarf surface plus the dynamic readjustments will produce strong magnetic fields throughout this envelope, and it is reasonable to suppose that they can result in a very high flux of suprathermal particles at the surface. Protons more energetic than 0.63 MeV can produce surface neutrons from $^{14}\mathrm{C}(p, n)^{14}\mathrm{N}$. Thus, if the surface layers can be stable and become contaminated once again by infalling hydrogen, one might have hot spots involving large bombardments of MeV-range protons. Fluxes of about $10^{27}\ \mathrm{cm}^{-2}$ of few-MeV protons will liberate neutrons from all ^{14}C within about $0.05\ \mathrm{g\ cm}^{-2}$ of the surface. If hydrogen is again the dominant constituent of the skin, these neutrons may be largely captured by protons, yielding deuterium. If the activity is at any one time concentrated in hot spots, the deuterium will grow to about $10^{-2}\ N_{\mathrm{H}}$, whereafter it will be converted to ^{3}He by the reactions $^2\mathrm{H}(p, \gamma)^3\mathrm{He}$, $^2\mathrm{H}(^2\mathrm{H}, n)^3\mathrm{He}$, and $^2\mathrm{H}(^2\mathrm{H}, p)^3\mathrm{H}$. What we describe are fusion reactions fed by nonthermal fluxes of surface protons (and deuterium). If, as a rough example, $N_{\mathrm{H}}/N(^{14}\mathrm{C}) \simeq 10^2$ in the surface skin, one might achieve $N_{\mathrm{H}}/N(^3\mathrm{He}) \simeq 10^3$ in the same skin. If ^{4}He is absent in this accreted and accelerated hydrogen and if it was absent in the original dwarf, the surface could appear to be helium-weak, and the helium present would be ^{3}He. These events could be related to the fantastic ^{3}He Ap stars 3 Cen A (Sargent and Jugaku 1961) and ι Ori B (Dworetsky 1973). One advantage is that the surface power required is, though large, not excessive. A flux of $10^{27}\ \mathrm{cm}^{-2}$ of 2-MeV protons requires $3 \times 10^{21}\ \mathrm{ergs\ cm}^{-2}$ of surface energy, which averages a surface luminosity of $10^{34}\ \mathrm{ergs\ s}^{-1}$ if it occurs over a 10^3-year period over the entire surface of an object with a radius $R = 10^{11}$ cm. Mixing of the surface skin with underlying material would, of course, increase these requirements.

As a related point, we note that *any* star enriched in surface ^{13}C has a possibility of surface neutrons from $^{13}\mathrm{C}(p, n)^{13}\mathrm{N}$. The low threshold (3.0 MeV) compared with abundant species makes this feasible with few-MeV protons and, fascinatingly, the ^{13}C is not destroyed. It acts only as a catalyst for conversion of protons to neutrons.

VI. ANOMALOUS N AND O COSMIC RAYS

To conclude this paper we wish to turn to related ideas in the areas of cosmic rays and cosmic gamma rays. McDonald *et al.* (1974) have discovered an anomalous low-energy (few-MeV per nucleon) component of the cosmic radiation. It is dominated by oxygen and nitrogen, and they suggest that they may have discovered a different type of galactic cosmic-ray source. Our considerations show how plausible this would be for some novae. If the dwarf were C and O, and if $2 < x < 4$, the thermonuclear runaway makes primarily N and O; therefore, if the shock wave accelerates low-energy cosmic rays, the preponderance of O and N is understandable. Even if $x > 4$, one still finds N and O considerably in excess of C, but in this case N may exceed O. Therefore, the N/O ratio in this cosmic-ray component is quite important. There is also a great opportunity for isotopic analysis, for many possibilities peculiar to this explanation exist. What carbon there is should be predominantly ^{13}C. The ^{15}N and ^{17}O should also be overabundant and, depending upon the value of x and the extent of the pre-explosive burning, may be the dominant isotopes of their respective elements. Unfortunately an unambiguous prediction is not possible. Perhaps only our *r*-process scenario is violent enough to accelerate abundant cosmic rays, in which case the cosmic rays might sensibly have an *r*-process appearance among the heavies. If so, their lifetime must be great enough for the ^{14}C to have decayed so that the dominance of O and N is obtained. Colgate and Johnson (1960) developed the shock-acceleration idea primarily for the more energetic cosmic rays, and we do not wish to debate its effectiveness here.

VII. GAMMA-RAY BURSTS

The novae may also be the source of the bursts of γ-rays observed by Klebesadel, Strong, and Olson (1973). The energy of these bursts is about 10^{40} ergs if their sources are at 1 kpc distance, and that is a small fraction of the prompt energy release in the thermonuclear runaway. Calculations (Starrfield *et al.*) show the initial shock to accelerate the surface to 1000 km s^{-1}, and it may be that the shock will also produce hard photons. Colgate (1974) has discussed the mechanism for supernova shocks. The expansion slows and falls back onto the dwarf in Starrfield's models, giving a second accretion shock some seconds after the initial shock. The accretion shock could be the secondary peak observed by Klebesadel *et al.* several seconds after the original burst. The radioactivity γ-ray lines recently discussed by us (Clayton and Hoyle 1974) are probably not of relevance here, because the object is too small initially and the time scales are too short; however, the sudden expansion and fall back of the outer envelope may release enough trapped suprathermal radiation generated by the ^{14}O positrons to influence the high-energy portion of the burst. With the very high rate of positron emission, the radiation field in the radiation-pressure–dominated atmosphere may maintain a high-energy tail as Compton scatterings attempt to degrade the radiation. This same initial shock is probably the one to accelerate the cosmic rays, but the event is sufficiently violent that heavy magnetic activity in the postnova surface may be the source instead.

These remarks close a rather speculative paper. It must be so, for our reasoning has led us to so many interesting problems that they cannot all be solved at once. This research has been supported by the National Science Foundation under grant GP-18335 and by NASA under grant NSG-7015.

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