The anthropic significance of the existence of an excited state of ^{12}C

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Were it not for the presence of an excited state of ^{12}C at 7.6 MeV, at the endpoint of the triple-alpha reaction, it would be difficult for stars to manufacture carbon and heavier elements. Calculations using modified triple-alpha rates test the sensitivity of stellar nucleosynthesis to the exact position of this excited state, and allow an empirical assessment of its importance in the anthropic principle in cosmology.

THERE has been much discussion of the 'coincidences' associated with the nuclear resonance levels of carbon and oxygen, which are essential for biological evolution, in relation to the anthropic principle[1]. The significance of such discussions lies in the fact that they deal with physical quantities within the realm of experimentally verifiable physics (rather than, say, with the yet uncertain physics of the early Universe). In particular, considerable attention has been focused on the 0^+ excited nuclear state of ^{12}C, at 7.644 MeV, which lies just above the energy of ^8Be plus an α-particle. In a truly remarkable prediction, Hoyle concluded from the observed cosmic-abundance ratios of ^{16}O:^{12}C:^4He that such a resonant level should exist. This has been confirmed subsequently by experiment[2-4].

As is consistent with the anthropic principle[1,5], the energy of the resonant level of ^{12}C is required to have the value it does, to ensure carbon production and the consequent development of carbon-based life. In a broader context, the location of the resonant level of carbon is the middle of three 'coincidences'. The first of these is the fact that the decay lifetime of ^8Be is about four orders of magnitude longer than the time required for two α-particles to scatter past one another in a non-resonant manner. This ensures the build-up of a small concentration of ^8Be, which can come into equilibrium[6], thus allowing its coexistence with ^4He. The third 'coincidence' is the fact that the energy level of ^{16}O at 7.1187 MeV is non-resonant, being below the combined energy of $^{12}C+\alpha$ (at 7.1616 MeV). This ensures that a significant fraction of the ^{12}C created will not be destroyed by α-particle capture.

In this exploratory work, we examine the question of how hypothetical changes in the location of the carbon 0^+ nuclear level might affect nucleosynthesis, carbon production, and its mixing into the interstellar medium (ISM). We note that a change in the nuclear energy levels should really be a consequence of changes in strengths of the fundamental interactions (strong, electromagnetic and so on). Such fundamental changes would affect not only the 0^+ level of ^{12}C but also many other nuclear energy levels. Indeed, these changes might result in a completely different structure and evolution of our Universe, and hence the incorporation of all of these changes is both beyond the capability of present-day theories of nuclear physics and certainly beyond the scope of this paper. We therefore limit ourselves to considerations of the anthropic argument that are related to changes in carbon production resulting from changes in the location of the 7.644-MeV level of ^{12}C. Calculations have been performed both for core triple-alpha burning and for shell helium burning in a thermally pulsing, asymptotic-giant-branch (AGB) star.

Core He burning in massive stars

One possible site of carbon production in stellar interiors is the core, and later the adjoining layers, of massive stars. Although in later phases of the evolution of stellar cores most of the products of helium burning will be processed to even heavier nuclei, there always remains carbon- and oxygen-rich matter that will be returned to the interstellar medium in the final supernova explosion. At the present age of the Galaxy, supernovae are probably not the main source of carbon production; rather, carbon production is expected to occur in thermal pulses in the shells of AGB stars. However, in the very early stages of galactic history, they were the only source, because less massive stars had not yet evolved far enough to return carbon to the ISM. It seems most appropriate, in the context of the anthropic principle, to investigate all possible sites of carbon production.

We have evolved a $20\text{-}M_\odot$ star through the completion of core helium burning, using a modified 0^+ level of ^{12}C, to identify the effects both on the amount of carbon produced and on the evolution. We evolve essentially the same model star as was considered by Truran and Weiss[7] in the context of supernova 1987A, using the same input physics and evolution code as described therein.

The only significant difference from the calculation of ref. 7 is the treatment of the triple-alpha process. In the code, the formula for the energy generation rate by this process is[8]

$$\varepsilon_{3\alpha} = \rho^2 Y^3 T_9^{-3} \exp(26.68 - 42.94/T_9) + \rho^2 Y^3 T_9^{-3} \exp(29.90 - 274.33/T_9) \quad (1)$$

where the first term arises from the 7.644-MeV resonance and the second from the 9.64-MeV resonance. The latter state does not contribute significantly for ordinary stellar burning conditions, and is usually neglected. In equation (1), ε is the energy generation rate in erg $g^{-1}\,s^{-1}$, ρ the density in g cm^{-3}, Y the mass fraction of helium, and T_9 is the temperature in units of 10^9 K. The term $-42.94/T_9$ in the argument of the first exponential function arises from $-\Delta E/kT$, where k is the Boltzmann constant, and ΔE is the energy difference between a carbon nucleus in the 0^+ state and three α-particles (see, for example, ref. 9), which amounts to 370 keV. The equivalent term in the second exponential function is that for the 3^- state, where the energy difference is 2,370 keV. It can be seen immediately that if the lower resonance state did not exist, the temperature would have to be 6.5 times higher to make the higher resonance comparably effective. However, at such a temperature, which would be close to 10^9 K (as compared to $\geqslant 10^8$ K in standard helium-burning cores), a greater variety of nuclear reactions involving heavier nuclei can occur, and such a star would evolve very differently from ordinary stars.

For the first example, we investigated the effect that would result from the total non-existence of the 0^+ resonance. We considered a star of typical population I composition: $X = 0{\cdot}739$, $Y = 0{\cdot}240$ and $Z = 0{\cdot}021$ where X is the mass fraction of hydrogen and Z is the mass fraction of all elements except hydrogen and helium. Thus, the initial carbon abundance by mass was ~0·005 and that of oxygen was ~0.010. This would of course be inconsistent with a conclusion that carbon cannot be created in a stellar environment under these circumstances; however, the initial abundance is much lower than that produced during ordinary helium burning, and our calculations confirmed that the results do not depend on the initial amount of carbon.

The evolution proceeded as follows. After the star completed its hydrogen-burning phase, the core contracted and heated up in the usual manner. In a standard comparison star, with the 0^+ level included at its normal energy, helium burning was initiated at $\sim 1.5 \times 10^8$ K, with the $3\alpha \rightarrow {}^{12}C$ reaction dominating over the competing ${}^{12}C(\alpha, \gamma){}^{16}O$ reaction, thereby converting helium mainly into carbon. (Subsequently, when the helium abundance had decreased and the temperature increased, the ${}^{12}C(\alpha, \gamma){}^{16}O$ reaction started to dominate and the carbon abundance decreased from a maximum of ~50% to ~10–20%.) In our present model, the ${}^{12}C(\alpha, \gamma){}^{16}O$ reaction alone proceeded at about the same temperature, consuming all the initial carbon within less than 10,000 years. At that point, the star had effectively corrected the initial inconsistency in carbon abundance. The next reaction to be considered is then ${}^{16}O(\alpha, \gamma){}^{20}Ne$. The core contracted further until it reached a temperature of 2.8×10^8 K, at which point oxygen was burned. The core then consisted of helium and heavier nuclei, with no trace of carbon or oxygen; the temperature at this stage was already as high as it is in normal stars at the end of helium burning.

We did not follow the evolution much further, as it was clear that the core would now contract rather quickly to attain a temperature of $\sim 10^9$ K. At this temperature a significantly more complex model of nucleosynthesis would be necessary to follow all of the processes taking place. We can conclude that if the 0^+ level did not exist at all, even primordial carbon would be destroyed in the cores of massive stars. Even at temperatures sufficiently high to ensure that the triple-alpha reaction would proceed through the 9.64-MeV level, any ${}^{12}C$ formed would be processed up an α-particle chain to intermediate and heavy nuclei.

For our next example, we included the 0^+ resonance, but at an energy difference with respect to ${}^8Be + \alpha$ of 860 keV, as opposed to the true difference of 370 keV. The evolution was similar to that described above except that now the triple-alpha reaction was able to proceed at the same temperature as the ${}^{16}O(\alpha, \gamma){}^{20}Ne$ reaction, in such a way that it formed carbon, which was converted immediately into oxygen and then into neon. Ultimately, the core matter was again carbon- and oxygen-free, but showed a slightly smaller helium abundance.

We then reduced the 0^+ level further, to an energy difference of 647 keV. The model now exhibited a distinct ${}^{12}C(\alpha, \gamma){}^{16}O$ burning phase, with some contribution from the triple-alpha process. Carbon was again destroyed almost completely except for a trace mass abundance of 10^{-4}, but the oxygen abundance increased to 0.02. This means that, in addition to the initial carbon abundance of 0.005, the same mass fraction of helium was burned to ${}^{12}C$ and beyond. If the ${}^{12}C(\alpha, \gamma){}^{16}O$ reaction alone were to operate, the decrease in helium mass fraction would be only one third of that of carbon. Indeed, the energy liberated by the triple-alpha process was twice as large as that from the ${}^{12}C(\alpha, \gamma){}^{16}O$ reaction and nine-times larger than that from the ${}^{16}O(\alpha, \gamma){}^{20}Ne$ reaction. This confirms the fact that the triple-alpha process is indeed operating. The detailed behaviour seems to be somewhat dependent on the initial abundances of C and O. The final state of the model reflected the fact that helium eventually is converted into oxygen by the chain of reactions $3\alpha \rightarrow {}^{12}C \rightarrow {}^{16}O$, with the equilibrium value of carbon being extremely close to zero. We estimate that the model would ultimately have burned oxygen via the ${}^{16}O(\alpha, \gamma){}^{20}Ne$ reaction, but that some oxygen could survive the helium-burning phase. We did not follow the evolution after carbon had reached its equilibrium value.

In a further experiment, we used a 0^+ energy difference of 430 keV. In this case the 3α process dominated at the beginning of helium burning, and carbon abundance increased from its primordial value to 9.5% by mass. This is an increase by a factor of almost 20. However, when this abundance level was reached in the core, the central temperature was high enough (2×10^8 K) for the ${}^{12}C(\alpha, \gamma){}^{16}O$ reaction to become dominant, and carbon decreased again, until finally all helium and carbon in the convective core (10% of the stellar mass) had been converted into oxygen. Thus, in its further evolution, the core of the star (in which all subsequent nuclear reactions up to the final collapse will occur) would be carbon-free. However, whatever the final structure and composition of the core might be, it will always be overlain by a partially burned helium shell. At the end of helium burning, this shell contained ~6% of the stellar mass (see Fig. 1). Within this shell, carbon is present with a maximum abundance by mass of ~10% and an average abundance of half this value. Thus, at the time of the supernova explosion, we estimate that 5×10^{-4} $M_\odot$ of fresh, newly created carbon would be ejected into the ISM. This value is very low compared with the amount of carbon produced in a real 20-$M_\odot$ star, but our result nevertheless indicates that a shift of the energy difference from 370 to 430 keV still allows carbon production.

Thus it is evident that carbon production in the cores of massive stars and its dependence on the location of the 0^+ level involves very similar considerations to those influencing the amount of carbon remaining after helium burning as a function of the exact ${}^{12}C(\alpha, \gamma){}^{16}O$ rate. Indeed, as there exist two competing processes (one carbon-producing and the other carbon-consuming), the final carbon abundance depends on the relative efficacy of these processes. When it was determined several years ago that the ${}^{12}C(\alpha, \gamma){}^{16}O$ reaction rate had to be increased[10], thereby making this process more effective with respect to $3\alpha \rightarrow {}^{12}C$, the carbon abundance produced in stellar models was found to decrease accordingly by roughly a factor of two to three. (Note that recent experiments, however, indicate a lower ${}^{12}C(\alpha, \gamma){}^{16}O$ rate (W. Fowler, personal communication).) In our numerical experiments, we basically achieve the same end by making the $3\alpha \rightarrow {}^{12}C$ reaction less effective. The features of the helium-burning phase are thus both easy to understand and rather predictable.

In all these calculations we have increased the energy difference between the (${}^8Be + {}^4He$) and 0^+ states. Making an anthropic statement that requires the 0^+ resonance to be at its observed level, however, raises also the question of how carbon

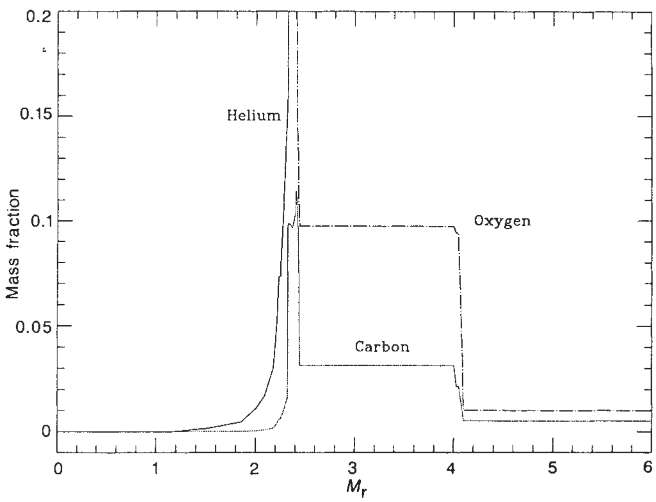

FIG. 1 The mass fractions of helium, carbon and oxygen in the helium core of a 20-$M_\odot$ model star at the end of central helium burning, as a function of the internal mass fraction M_r, for the case in which the energy of the 0^+ level of ${}^{12}C$ is taken to be 430 keV above the sum of the masses ${}^8Be + \alpha$. note that the ordinate extends only to 0.2.

production is affected in the case of a smaller energy difference. From the discussion above, the answer can be predicted easily: more carbon would be produced during helium burning. To answer the question more quantitatively, we performed another experiment in which the 0^+ level was lowered by 60 keV. The result is surprising. At the end of the core helium-burning phase, carbon had a mass fraction of 0·794, which is roughly four times higher than normal. Comparing this with the result of increasing the level by 60 keV, it appears that carbon production is not strongly favoured by nature, because a small reduction in the energy difference would lead to a relatively much greater increase in carbon abundance than the respective decrease that results from an equivalent increase in the energy difference. In terms of the anthropic principle, one might say that "things could be worse, but they could easily be much better."

We can make some remarks on the implications of our numerical experiments for the global behaviour of the models. The higher the energy of the 0^+ level, the more the core contracted, and in consequence, the more the envelope expanded. In the first model (no 0^+ level), for example, the star reached the red-giant branch before carbon had been burned, whereas in the final model it was still at a temperature of 10,000 K at the end of helium burning. When the energy of the resonance is decreased, the convective core increases in mass. This is all a result of the fact that 'blocking' the triple-alpha process leads to a decreased energy output of the core.

Shell He burning in AGB stars

Observations indicate that the surfaces of AGB stars become contaminated with carbon, and it is believed that these AGB stars are a major source of carbon (as well as many other heavy elements) in galaxies. Theoretical investigations have demonstrated that the appearance of carbon at the stellar surface is a consequence of a thermal instability occurring in the helium-burning shell which surrounds the degenerate carbon-oxygen (C-O) core[11]. The carbon-enhanced surface material is introduced into the ISM by relatively rapid mass loss (timescales $\tau_{\text{mass loss}} \ll \tau_{\text{nuclear}}$) which occurs as a consequence of a pulsational instability in the expanded red-supergiant envelope[12,13]. We have studied how a change in the energy of the carbon 7.644-MeV level can affect both the energetics of the AGB thermal instability and the nucleosynthesis that occurs during the subsequent thermal runaway.

We consider a 5-$M_\odot$ AGB star with a 0.96-$M_\odot$ C-O core, and we assume that this star initially had a solar metallicity. This assumption is again potentially inconsistent with the carbon energy level being different from its true value, but we suggest that this should not influence our conclusions significantly. The AGB star has been modelled through a thermal pulse using the evolutionary code described by Iben[14]. Three sequences have been calculated: in sequences I (the standard sequence), II and III we have assumed that the 0^+ level of carbon is 370, 430 and 647 keV, respectively, above the ^{8}Be$+\alpha$ energy.

This AGB star will spend ~90% of its lifetime burning hydrogen into helium in a thin shell. The hydrogen-burning shell deposits this helium (as well as some nitrogen, via the CNO cycle) into the helium-rich (or helium- and carbon-rich) region that lies above the degenerate C-O core. When a sufficient quantity of helium accumulates in this region, triple-alpha burning commences in a runaway fashion, and in the standard sequence most of the runaway energy is supplied by the triple-alpha reaction. A convective shell forms below the hydrogen-burning region, and this shell provides fuel (helium, carbon and nitrogen in the standard sequence) for the runaway occurring at the base of the shell. When fresh ^{14}N is introduced into the convective shell, the luminosity from the ^{14}N$(\alpha, \gamma)^{18}$O reaction will temporarily exceed that from the $3\alpha \rightarrow {}^{12}$C reaction.

The byproducts of the runaway (carbon, oxygen and neon) are distributed throughout the convective layer during this phase. When the convective shell is at its maximum extent (in the stellar mass coordinate), only one ^{12}C nucleus in the shell is destroyed (by α-particle capture) for every 50 that are created (by the triple-alpha process). The composition of the shell is then 83% helium and 15% carbon (by mass). This carbon at the upper edge of the convective shell is eventually mixed through the base of a convective envelope to the stellar surface, and subsequently into the ISM.

In the models of sequence II, the evolution of the thermal pulse is similar to that in the standard sequence. The reduction in the triple-alpha reaction rate causes the pulse to develop somewhat more slowly, and hence makes the thermal instability ignite helium under conditions of higher pressure and density (and at a smaller radial coordinate) compared with the standard sequence. Consequently, a more massive convective shell is produced, and a higher shell temperature allows both the $3\alpha \rightarrow {}^{12}$C and ^{12}C$(\alpha, \gamma)^{16}$O reactions to proceed more rapidly. In this case, when the convective shell reaches it maximum extent, ^{12}C is created approximately 20-times faster than it is destroyed, and carbon and helium are still the major constituents of the convective shell. In fact, because the convective shell itself is more massive, the amount of carbon mixed to the stellar surface during a later phase may be larger in this sequence than in the standard sequence.

The situation is radically different for sequence III. For sequences I and II, the development of the thermal pulse depends ultimately on the ignition of the $3\alpha \rightarrow {}^{12}$C reaction in the helium-rich region overlaying the degenerate C-O core. In sequence III, however, the luminosity from the triple-alpha reaction is orders of magnitude smaller than the luminosity from α-particle capture on ^{12}C, ^{14}N or ^{18}O. The calculations show that any ^{12}C that is produced during the thermal pulse is quickly converted to ^{16}O. We find, therefore, that carbon production by AGB-star thermal pulses does not occur when the 0^+ level is moved as high as 647 keV above the ^{8}Be$+\alpha$ energy. It should be noted that the thermal pulse in sequence III was not modelled to completion, because of numerical difficulties arising in the models from the interplay between α-particle capture on ^{14}N and ^{18}O (which powers the runaway) and the rate at which unprocessed ^{14}N is introduced into the convective shell.

We note that the production of carbon also can be affected by the rate at which ^{12}C is destroyed in AGB-star models. It has been shown, for example, that the abundance ratio ^{16}O/^{12}C at the surface of a model star increases as the rate of the ^{12}C$(\alpha, \gamma)^{16}$O reaction increases[15]. Furthermore, we have considered the effect of an increase in the energy of the 0^+ level of ^{12}C on AGB models, but not the effect of a decrease. The latter would result in an enhanced rate of ^{12}C production, and would have to be evolved through (at least) several successive pulses to properly determine the extent to which ^{12}C becomes enhanced (above the 'standard' 15% mass abundance) in the AGB interior. Decreasing the 0^+ energy level would also make each thermal pulse weaker than in the standard model, and it is unclear whether these weaker pulses could provide the energy required to cause ^{12}C-enhanced material to be transported from the interior to the surface of a model AGB star.

Conclusions

On the basis of a series of numerical experiments, we have determined that a 60-keV increase in the location of the 0^+ level of carbon does not significantly alter the level of carbon production in stellar environments. Although the amount of carbon produced (relative to oxygen) is reduced, both in core burning and in shell burning, the strength of the thermal pulse in AGB stars is increased. This may increase the amount of interior (processed) material that is ultimately mixed to the stellar surface and therby lost to the ISM. Also, a decrease in the location of the 0^+ level by the same amount leads to significantly greater carbon production. If the nuclear energy level is increased by 277 keV or more, the results of nuclear burning are radically different and very little carbon is produced.

The implications of these results for evaluating the anthropic 'coincidence' on which our existence seems to rely are not entirely free from subjective feelings. Whether or not one must conclude that the 0^+ level has to be exactly where it is depends on whether we should regard a change of 60 keV as small or large. We believe that, although it is true that 60 keV is small compared with the spacing between the 7.644-MeV level and the next higher level at 9.64 MeV, this shift clearly represents a significant fraction of the energy difference between the 0^+ level and the energy of $^8Be+\alpha$. Thus, we believe that at least some formulations of the strong anthropic principle, which is based on the necessity of having the 0^+ level exactly where it is, is weakened significantly by our results. □

Received 20 March; accepted 25 May 1989.

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ACKNOWLEDGEMENTS. This work was supported in part by the NSF and by the National Center for Supercomputing Applications at the University of Illinois.

Nanometre-level analysis demonstrates that lipid flow does not drive membrane glycoprotein movements

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Nanometre-level analyses of the movements of membrane glycoproteins tagged with gold particles demonstrate that diffusing particles are not under the influence of a lipid flow, although a subset of particles which appear attached to the cytoskeleton are moving rearward.

DIRECTED motions of membrane proteins occur in antibody capping, cell migration and the assembly of the extracellular matrix, processes which are important in the immune response and organogenesis. It has been proposed that the driving force for these motions might be membrane flow[1,2] or cytoskeletal movements[3]. Analysis of glycoprotein movements at the molecular level can differentiate between these mechanisms, because the velocity and path of a glycoprotein provides a distinctive fingerprint of the molecular mechanism of its movement.

The membrane-flow model suggests that membrane lipid flows back from the leading edge of the cell to sites of endocytosis and is then recycled to the front of the cell again[1,2]. Membrane glycoproteins are supposed to float freely in the lipid bilayer, whereas large particles or aggregates of crosslinked glycoproteins, which diffuse slowly, will be swept rearward by the flow[1]. The rapid diffusion of small particles or uncrosslinked molecules counters the flow and prevents the development of a substantial concentration gradient. Nevertheless, the effect of lipid flow even on rapidly diffusing particles should be detectable in sufficiently precise measurements.

Other models propose that glycoproteins are driven by interaction with rearward-moving cytoskeletal structures[3-5]. Recent studies have shown that the actin cytoskeleton and drifting particles on the cell surface move rearward at the same velocity[3-6]. Crosslinked glycoproteins strongly bound to the cytoskeleton would diffuse slowly and be dragged rearward. Particles free of cytoskeletal interactions would diffuse more rapidly without rearward drift. Detection of a rearward drift of rapidly diffusing particles would therefore support the lipid-flow model, whereas its absence would be evidence against it.

Fluorescence photobleaching recovery (FPR) measurements have demonstrated both rapidly and slowly diffusing (or immobile) states of concanavalin A (con A) receptors on macrophages[7]. Even the mobile particles diffused too slowly, however, to be limited by only lipid viscosity and so must be restrained by additional, possibly cytoskeletal, forces[8,9]. FPR measurements do not discriminate between the two models because both predict that membrane glycoproteins tagged with multivalent ligands could exist in both rapidly and slowly diffusing states.

Previous observations have revealed the rearward drift of large particles on the surfaces of motile cells[10-12] but have not determined the role of lipid flow. A recently developed method, which measures the positions of smaller particles using video-enhanced microscopy[13,14], provides a more discriminating test. This method, developed by Gelles *et al.*[15], yields dynamic (30 Hz), precise measurements of the positions of 40-nm-diameter gold particles on a cell surface. We have observed that con A-coated gold particles bound to the surface of mouse peritoneal macrophages reversibly transfer between two modes, one of random diffusion at rates consistent with earlier FPR measurements but not undergoing rearward drift, and the other of rearward drift with slower diffusion. Both qualitative and quantitative considerations of these observations argue against the lipid-flow mechanism and in favour of a cytoskeletal model.

Glycoprotein diffusion and transport

When we added con A-coated gold particles to macrophages, they bound in a con A-dependent manner with two distinct modes of motion, random diffusion and directed transport