THE ASTROPHYSICAL JOURNAL, 509:L1–L3, 1998 December 10

THE ORIGIN OF HELIUM AND THE OTHER LIGHT ELEMENTS

G. BURBIDGE
Department of Physics, Code 0354, and Center for Astrophysics and Space Science, Code 0111, 9500 Gilman Drive, University of California at San Diego, La Jolla, CA 92093
AND
F. HOYLE
102 Admirals Walk Bournemouth BH2 5HF, Dorset, England, UK
Received 1998 August 20; accepted 1998 October 14; published 1998 November 4

ABSTRACT

The energy released in the synthesis of cosmic ^{4}He from hydrogen is almost exactly equal to the energy contained in the cosmic microwave background radiation. This result strongly suggests that the ^{4}He was produced by hydrogen burning in stars and not in the early stages of a big bang. In addition, we show that there are good arguments for believing that the other light isotopes, D, ^{3}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, and ^{11}B, were also synthesized in processes involving stars. By combining these results with the earlier, much more detailed work of Burbidge et al. and of Cameron, we can finally conclude that *all* of the chemical elements were synthesized from hydrogen in stars over a time of about 10^{11} yr.

Subject headings: cosmic microwave background — early universe — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

There are more than 320 stable isotopes in the periodic table. In our original work (Burbidge et al. 1957, hereafter B^{2}FH; see also Cameron 1957), we showed that nearly all of them, with the possible exception of the helium isotopes and D, Li, Be, and B, were synthesized by nuclear processes in stellar interiors. In the 1950s, there appeared to be several problems associated with explaining the observed abundances of these remaining nuclides, which we discuss in turn. We shall show here that another approach leads to the conclusion that very likely all of them have been synthesized in processes involving stars.

2. ^{4}He

In the 1950s, it appeared to us that there were two problems associated with explaining the origin of helium in its measured abundance through hydrogen burning. Assuming that the timescale of the universe is $\sim H_0^{-1}$, there was not enough time for a ^{4}He/H ratio of about 0.24 to be built up, if the luminosities of the galaxies remained at normal levels for 10^{10} yr. Second, there appeared to be no evidence that the energy released by this amount of hydrogen burning was present. The energy density of starlight of about 10^{-14} ergs cm^{-3} is well below the energy released in hydrogen burning, which, for a ^{4}He/H ratio of 0.243 (Pagel 1997; Isotov, Thuan, & Lipovetsky 1997) that we assume to be universal, is 4.37×10^{-13} ergs cm^{-1}. In deriving this quantity, we have taken the mean density of baryonic matter associated with galaxies to be 3×10^{-31} g cm^{-3}. This number has been obtained from the counts of galaxies, and we assume that baryonic dark matter in the form of massive halos, etc. (with 10 times the visible mass), is present. Here we have put $H_0 = 60$ km s^{-1} Mpc^{-1}.

In the 1950s, Bondi, Gold, & Hoyle (1955) argued that the large amount of undetected energy, which must be present if the helium has been synthesized in stars, must reside in the far-infrared spectrum, while Burbidge (1958) speculated that perhaps there was an earlier short-lived phase in the evolution of galaxies in which they were much more luminous, or else possibly the true helium abundance was lower than 0.24, because most of the mass is tied up in low-mass stars in which He/H < 0.24.

Of course, the solution to the He problem that became popular was that which Gamow, Alpher, & Herman proposed earlier (cf. Alpher & Herman 1950), that the helium was made in a hot big bang some 10^{10} yr ago. Several calculations following this work and starting with Hoyle & Tayler (1964), Peebles (1966), and Wagoner, Fowler, & Hoyle (1967) demonstrated this. We have now reached the stage where it is argued that the *existence* of He and the other light isotopes is taken, together with the microwave background radiation, as primary evidence in favor of the standard, hot, big bang cosmological model. However, this argument is only powerful if there is no other way to explain the helium abundance and the microwave background radiation.

In 1941, McKellar (1941) showed that there must be a radiation field present in the Galaxy with a temperature between 1.8 and 3.4 K. Penzias & Wilson's (1965) measurements, followed by others and culminating in the *COBE* observations by J. Mather and his colleagues (cf. Fixsen et al. 1996), have shown that the cosmic microwave background (CMB) has a blackbody form at least out to radio wavelengths with $T = 2.728$ K. The hot big bang cosmological model is not able to predict the temperature (cf. Turner 1993). But what is remarkable about the result that we have described here is that the energy density of the *observed* blackbody radiation is extremely close to the energy density expected from the production of helium from hydrogen burning. We showed earlier that this energy is 4.37×10^{-13} ergs cm^{-3}, and when this energy is thermalized, the temperature turns out to be $T = 2.76$ K.

While the value of the baryonic density in galaxies and their environs is not known with anything like the precision with which the blackbody temperature is measured, it is clearly not very different from $\rho = 3 \times 10^{-31}$ g cm^{-3} ($H_0 = 60$ km s^{-1} Mpc^{-1}, and dark/luminous baryon ratio $\approx$10), and, of course, the calculated temperature is only proportional to $\rho^{1/4}$. Indeed, it might be argued that the CMB temperature gives a more precise measure of the true mass density of baryonic matter in the universe than can be obtained by estimating the mass in galaxies.

We conclude that this result, based on two simple observational arguments, strongly suggests that the helium and the CMB were produced by hydrogen burning in stars. This requires a time much greater than 10^{10} yr, and there must be a physical mechanism operating that is able to thermalize the radiation that is initially released through hydrogen burning as ultraviolet photons from hot stars in starburst situations in galaxies. We have shown elsewhere that both of these conditions are fulfilled within the framework of the quasi–steady state cosmology (QSSC) (Hoyle, Burbidge, & Narlikar 1993, 1994a, 1994b, 1995). In the QSSC, the universe is in a sequence of oscillations of period Q superposed on a general universal expansion of period P. In our model, $Q \approx 10^{11}$ yr and $P \approx 10^{12}$ yr. These timescales correspond to the lifetimes of main-sequence dwarf stars with masses less than 0.7 and 0.4 $M_{\odot}$, respectively, thereby greatly enhancing the importance of dwarf stars in cosmogony. We conclude that ^{4}He in the cosmos is most likely a result of stellar nucleosynthesis. Given that this most abundant nucleus among the light elements is a result of stellar activity, it is then natural to ask whether the other light isotopes can also be due to processes involving stars.

3. ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, AND ^{11}B

Much work has been done on these nuclides in recent years. It is generally accepted that ^{6}Li, ^{9}Be, ^{10}B, and ^{11}B were produced in spallation reactions of high-energy protons on ^{12}C and ^{16}O with the energy ultimately coming from galactic processes as we originally proposed (B^{2}FH). Reeves, Fowler, & Hoyle (1970) showed that galactic cosmic rays are an important ingredient. The most modern work shows that it is the C and O that bombard the protons and α-particles. The Be and B abundances are proportional to the Fe/H ratio in subdwarfs, and Vangioni-Flam et al. (1996) have shown that spallation by high-energy C and O can account for this. The high-energy C and O nuclei are ejected in the winds from massive stars and supernovae.

What about ^{7}Li? The early suggestion (Reeves et al. 1970) that spallation is responsible gives a ^{6}Li/^{7}Li ratio of order unity, but in the solar system, ^{6}Li/^{7}Li $\simeq 10$. This is one of the reasons why it has been argued that Li^7 at least is due to big bang nucleosynthesis. This argument has been supported by the claim that there is a "plateau" at ^{7}Li/H $= 1.7 \times 10^{-10}$ in a sample of Population II stars that are greater than 10^{10} yr old (Spite & Spite 1985). However, it is now known that this plateau is breached and that several stars have ^{7}Li/H $< 10^{-10}$ (Bonifacio & Molero 1997). Ryan et al. (1996) conclude that there is an intrinsic spread in the ^{7}Li abundance due to influences other than uniform nucleosynthesis in a big bang. We must also not forget that while it is generally believed that susceptibility to destruction prevents ^{7}Li from being synthesized in stars, the observation that there is a class of lithium-rich supergiants (cf. WZ Cas; McKellar 1940) shows that stellar processes may be responsible, as was suggested in a complicated scenario by Cameron & Fowler (1971).

Boesgaard & Tripicco (1986) looked at the Li abundance as a function of [Fe/H] for both Population I and old disk stars. They found that the Li abundance could be very different in stars where the [Fe/H] abundance has the solar value but that there is an absence of stars that are Li rich but have low values of [Fe/H] (see also Rebolo et al. 1988 and Balachandran 1990). The abundances and isotope ratios of Li in the interstellar gas have been determined most recently by Lemoine, Ferlet, & Vidal-Madjar (1995). They have concluded that there must be an extra source of ^{7}Li in the Galaxy. It is now clear from the observations that there may be at least three possible effects that have contributed to the observed Li abundance. They are (*a*) stellar processing, which tends to deplete Li, (*b*) galactic production, which tends to build Li, and (*c*) big bang nucleosynthesis. From the observations, the relative importance of (*a*), (*b*), and (*c*) is not yet clear. However, in view of our earlier arguments concerning the origin of ^{4}He, we consider it likely that (*c*) is not operating. Thus, we believe that (*a*) and (*b*) alone can explain the Li abundance and that further observational investigations will show this.

4. D AND ^{3}He

The light isotope ^{3}He is produced in large quantities in dwarf stars where the masses are not large enough for it to be destroyed by ^{3}He (^{3}He, 2p) ^{4}He. It is also the case that there is a class of stars in which it has been shown from measurements of the isotope shift that most of the helium in their atmospheres is ^{3}He. These stars include 21 Aquilae, three Centaurus A, and several others (Burbidge & Burbidge 1956; Sargent & Jugaku 1961; Hartoog & Cowley 1979; Stateva, Ryabchikov, & Iliev 1998). The stars are peculiar A, F, and B stars having He/H abundances that are $\sim\frac{1}{10}$ of the normal helium abundance. The ^{3}He/^{4}He ratio can range from 2.7 to 0.5. These stars occupy a narrow strip in the (log g, $T_{\rm eff}$)-plane between the B stars with strong helium lines and those with weak helium lines that show no evidence for the presence of ^{3}He. However, the detection of ^{3}He from the isotope shift will fail if the ^{3}He/^{4}He ratio is $\lesssim 0.1$. Thus, many of the weak helium-line stars may well have ^{3}He/^{4}He abundance ratios far higher than the abundance ratio that is normally assumed to be present, namely, ^{3}He/^{4}He $\approx 2 \times 10^{-4}$. The high abundance of ^{3}He in these stars has been attributed by G. Michaud and his colleagues to diffusion (Michaud et al. 1979 and earlier references). Whether or not this is the correct explanation, what these results do tell us is that stellar winds from such stars will enrich the interstellar gas with ^{3}He in large amounts. This ^{3}He is in addition to the ^{3}He that will be injected from dwarf stars. The final abundance required is ^{3}He/H $\approx 2 \times 10^{-5}$. It has been argued by those who believe that ^{3}He is a product of big bang nucleosynthesis that there has not been time to build up the required abundance by astrophysical processes. However, not only do we not know what the rate of injection from stars is, but in the QSSC, the timescale for all of this stellar processing is $\sim 10^{11}$ rather than $H_0^{-1} \approx 10^{10}$ yr. Thus, we believe that ^{3}He may very well have been produced by stellar processes.

We turn finally to the production of deuterium. It has been argued that D cannot be synthesized by spallation or photodisintegration in supernova outbursts (Epstein, Lattimer, & Schramm 1976; Sigl et al. 1995). Recently, however, Fuller & Shi (1997) have argued that antineutrinos ν_e^- can give rise to deuterons through $\nu_e^- + p \rightarrow n + e_\nu^+$, followed by $n(p, \gamma)$D-reactions in the collapse of supermassive stars ($M \geq 5 \times 10^4$ $M_{\odot}$) in the early history of galaxies. This mechanism may be important, but in view of the fact that the ^{3}He/H and D/H ratios are very similar, and because we believe that the ^{3}He is likely to be produced by low-mass stars, we believe that the most likely source of the cosmic deuterium is the dwarf stars.

It is known that the dwarf M stars are a major constituent of normal galaxies. They have extensive convective envelopes, and thus they are likely to have outer layers in which extensive flare activity takes place. A very good example is the large UV flare in the red dwarf AU Microscopii, which has just been reported (Katsova, Drake, & Livshits 1998). In our view, it is the cumulative effect of stellar winds and flares from these low-mass stars that has led to the build up of the deuterium.

It is easily shown that the amount of energy required to generate a D/H ratio $\sim 10^{-5}$ through flaring and ejection from dwarf stars is not very large. The energy required to produce D in stellar flares through the generation of neutrons and the subsequent capture by protons turns out to be close to 6×10^{18} ergs per gram of D, which is much the same as the energy release involved in hydrogen burning to ^{4}He. For a universal mass density of 3×10^{-31} g cm^{-3}, the energy requirement is then 1.8×10^{-17} ergs cm^{-3}. This is very small compared with the energy of starlight, which, at present, is $\sim 10^{-14}$ ergs cm^{-3} and which, in the QSSC, will build up to 10^{-13} ergs cm^{-3} in the full cycle. Thus, the energy requirement in the production of D is for a small fraction of the available energy that is to go into the generation of neutrons.

Deuterium is known to be produced in solar flares (Chupp et al. 1973; Anglin, Dietrich, & Simpson 1973), and early work by Coleman & Worden (1976) has shown how much mass can be ejected from the dwarf stellar component. They estimated that for a typical galaxy containing 10^{11}–10^{12} dwarf M stars, the mass-loss rate will amount to about 0.1 $M_\odot$ yr^{-1} from the dwarfs. If we add to this the fact that the programs now underway to detect faint stars through microlensing are now showing that the number of dwarf stars is very large, and the fact that in the QSSC cosmology, the timescale for the buildup of D in the interstellar gas is much greater than 10^{10} yr, a large amount of interstellar gas that is enriched in deuterium will be produced in a timescale corresponding to a cycle of oscillation Q in the QSSC, i.e., in 10^{11} yr.

Of course, in the same period, the deuterium contained in gas that is recondensed into stars will be destroyed, so that the final abundance will depend on how much uncondensed gas remains. More measurements are required of D/H both in the gas in our Galaxy (cf. Linsky et al. 1993, 1995) and elsewhere. Much has been made recently of the D/H ratio determined in the absorption-line spectra of QSOs with large redshifts. The value obtained by D. Tytler and his colleagues (Tytler, Fan, & Burles 1996; Burles & Tytler 1996), D/H $\lesssim 2 \times 10^{-5}$, is the best estimate that has been made so far for extragalactic material, and this has been discussed only in the context of big bang cosmology. In the QSSC, the absorbing clouds that give rise to the absorption spectrum may also lie at an earlier epoch in the cycle. However, as we have discussed elsewhere (Hoyle & Burbidge 1996), there is independent evidence that many QSOs may not lie at the distances indicated by their redshifts, so the epoch to which these values of D/H correspond is not clear.

Our prediction is that with the deuterium made largely in stellar flares, there will be a range of values of the D/H ratio, with values of D/H $\sim 10^{-5}$ at the high end. We do not expect that the D/H ratio will have a constant value throughout an individual galaxy or throughout a cycle of the QSSC. Thus, a possible test is to look for differences in the D/H ratio both inside and outside our Galaxy.

5. CONCLUSION

We have shown that there are good reasons to argue that ^{4}He has been produced by hydrogen burning in stars and that the other light isotopes have also very likely been produced by astrophysical processes following stellar activity. Thus, provided that a timescale much greater than H_0^{-1} is available, as is the case in the QSSC, all of the chemical elements may well have been synthesized in stellar processes. The fact that the great majority of the 320 stable isotopes have been generated astrophysically has always made the idea that all of the isotopes were made this way very attractive.

REFERENCES

Alpher, R. A., & Herman, R. 1950, Rev. Mod. Phys., 22, 153
Anglin, J. D., Dietrich, W., & Simpson, J. 1973, ApJ, 186, L41
Balachandran, S. 1990, ApJ, 354, 310
Boesgaard, A., & Tripicco, M. J. 1986, ApJ, 303, L42
Bondi, H., Gold, T., & Hoyle, F. 1955, Observatory, 75, 80
Bonifacio, P., & Molero, P. 1997, MNRAS, 285, 547
Burbidge, E. M., Burbidge, G., Fowler, W. A., & Hoyle, F. 1957, Rev. Mod. Phys., 29, 547 (B^{2}FH)
Burbidge, G. 1958, PASP, 70, 83
Burbidge, M., & Burbidge, G. 1956, ApJ, 124, 655
Burles, S., & Tytler, D. 1996, ApJ, 460, 584
Cameron, A. G. W. 1957, Chalk River Rep. CRL-41
Cameron, A. G. W., & Fowler, W. A. 1971, ApJ, 164, 111
Chupp, E., Forrest, D., Higbie, P., Suri, A., Tsai, C., & Dunphy, P. 1973, Nature, 241, 333
Coleman, G., & Worden, P. 1976, ApJ, 205, 475
Epstein, R., Lattimer, J., & Schramm, D. 1976, Nature, 263, 198
Fixsen, D., et al. 1996, ApJ, 473, 576
Fuller, G., & Shi, X. 1997, ApJ, 487, L25
Hartoog, M., & Cowley, A. 1979, ApJ, 228, 229
Hoyle, F., Burbidge, G. 1996, A&A, 309, 335
Hoyle, F., Burbidge, G., & Narlikar, J. V. 1993, ApJ, 410, 437
———. 1994a, MNRAS, 267, 1007
———. 1994b, A&A, 289, 729
———. 1995, Proc. R. Soc. London A, 448, 191
Hoyle, F., & Tayler, R. 1964, Nature, 203, 1108
Isotov, Y., Thuan, T., & Lipovetsky, V. 1997, ApJS, 108, 1
Katsova, M., Drake, J., & Livshits, M. 1998, CfA preprint 4704
Lemoine, M., Ferlet, R., & Vidal-Madjar, A. 1995, A&A, 298, 879
Linsky, J., et al. 1993, ApJ, 402, 695
———. 1995, ApJ, 451, 335
McKellar, A. 1940, PASP, 52, 407
———. 1941, Publ. Dom. Astrophys. Obs. Victoria, 7, 15
Michaud, G., Martel, A., Montmerle, T., Cox, A. N., McGee, N. H., & Hudson, S. W. 1979, ApJ, 234, 206
Pagel, B. E. J. 1997, in The Universe at Large, ed. G. Munch, A. Mampaso, & F. Sanchez (Cambridge: Cambridge Univ. Press), 343
Peebles, P. J. E. 1966, ApJ, 146, 542
Penzias, A., & Wilson, R. 1965, ApJ, 142, 419
Rebolo, R., Molaro, R., Abia, C., & Beckman, J. 1988, A&A, 193, 193
Reeves, H., Fowler, W. A., & Hoyle, F. 1970, Nature, 226, 727
Ryan, S., Beers, T., Deliyannis, C., & Thorburn, J. 1996, ApJ, 458, 543
Sargent, W. L. W., & Jugaku, J. 1961, ApJ, 134, 777
Sigl, G., Jedamsik, K., Schramm, D., & Berezinsky, V. 1995, Phys. Rev. D, 52, 6682
Spite, M., & Spite, F. 1985, ARA&A, 23, 225
Stateva, I., Ryabchikov, T., & Iliev, I. 1998, preprint
Turner, M. 1993, Science, 262, 861
Tytler, D., Fan, X. M., & Burles, S. 1996, Nature, 381, 207
Wagoner, R., Fowler, W. A., & Hoyle, F. 1967, ApJ, 148, 3
Vangioní-Flam, E., Cassé, M., Fields, B., & Olive, K. 1996, ApJ, 468, 199