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PHOTOEROSION AND THE ABUNDANCES OF THE LIGHT ELEMENTS

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ABSTRACT

The abundances of the rare light elements ^{2}H, ^{3}He, ^{7}Li, and ^{11}B are shown to be potentially affected by photoerosion. That process, involving the interaction of high-energy photons from galactic centers with atomic nuclei, will increase the abundances of ^{2}H, ^{3}He, and ^{11}B while lowering slightly those of ^{7}Li and ^{4}He. In some regions of galaxies the effects may be large enough to impact their chemical evolution. In particular this process may have enhanced the ^{2}H and ^{3}He abundances near the center of our Galaxy over and above those from the big bang, as well as the Galactic ^{11}B abundance over that from cosmic-ray spallation.
Subject headings: abundances — cosmic rays: general — cosmology

The abundances of the light elements ^{2}H, ^{3}He, ^{4}He, and ^{7}Li have provided tests of theories about elemental production mechanisms, including those which occurred just after the big bang. In particular, the standard hot big bang model (Wagoner, Fowler, and Hoyle 1967; Schramm and Wagoner 1977; Boesgaard and Steigman 1985; Yang *et al.* 1984) successfully explains the abundances of the light elements produced during the early minutes of the universe; those abundances have been used to place an upper limit on the baryonic density of a few percent of that required to close the universe. Enormous effort has gone into extrapolating back in time to deduce the relationship between the primordial abundances and those presently observed, but most studies have assumed that any process which destroys ^{3}He or ^{7}Li will also destroy ^{2}H by an even greater amount, based on the relative fragility of the ^{2}H nucleus.

Conversely, the isotopes ^{10}B and ^{11}B are thought (Reeves, Fowler, and Hoyle 1970) to have been produced by spallation resulting from the interactions of high-energy cosmic rays with the nuclei in the interstellar medium. However, this mechanism predicts (Audouze, Menezurz, and Reeves 1976) a ratio of $[^{11}\mathrm{B}]/[^{10}\mathrm{B}]$ of 2.4, whereas the observed value is 4.4. The traditional way to solve this problem has been to add an arbitrary low-energy spike to the Galactic cosmic ray spectrum. However, such a spike seems to serve no other function than to solve the boron problem.

In this *Letter* we note that photoerosion (Boyd and Ferland 1987), a process of photonucleon emission which occurs near active galactic nuclei (AGNs), would have quite different consequences on the abundances of the light elements from other processes usually considered. Furthermore, this process may have general relevance to galactic chemical evolution, since it has been hypothesized (Oort 1977) that all spiral galaxies may have been AGNs at some stage in their evolution; we examine this question in the context of our own Galaxy.

Since the photon spectrum in photoerosion is described by a power law, it can enhance considerably, over thermal processes, those processes which require high-energy photons. This can have a great impact on abundances of light elements; it more than compensates for the photodestruction of ^{2}H which would normally occur in regions of high photon density, resulting in a net *production* of ^{2}H. This feature could impinge on various models of big bang nucleosynthesis, e.g., the standard model mentioned above and those with nonuniform density (Alcock, Fuller, and Mathews 1987; Sale and Mathews 1987; Schramm and Wagoner 1977; and Wagoner 1973), which have the feature that they can produce the light element abundances with an average baryonic density equal to that required to close the universe.

Few AGNs have undergone sufficient scrutiny for an accurate determination of their ability to perform photoerosion. Thus we have assumed the parameters known to exist for one well-studied AGN, NGC 4151, as typical of those for all spiral galaxies for part of their evolutionary history. This assumption will allow us to develop the photoerosion scenario, and to assess its possible impact on the light element abundances in our Galaxy which would have existed if it did possess such properties for a significant fraction of its past. The photon number spectrum falls off as $E^{-2.7}$ (Baity *et al.* 1984), and the total flux with $E > 2$ MeV is 4×10^{16} photons cm^{-2} s^{-1} (Boyd and Ferland 1987) at a distance of 2 lt-days from the Galactic center. The region around a few lt-days is thought (Gaskell and Sparke 1986; Gusten *et al.* 1987) to contain molecular clouds; this is the region in which photoerosion would be expected to occur. It should be noted that, while NGC 4151 is a well-studied AGN, it is one of exceptionally low luminosity (Boyd and Ferland 1987). A more typical AGN would produce a photon flux greater by at least an order of magnitude.

The cross sections for the relevant reactions, which are only partially known, are shown in Table 1, along with the references from which they originated. Few data on cross sections of photon-induced deuteron production reactions of the type $^{A}\mathrm{X}(\gamma, {}^2\mathrm{H})^{A-2}\mathrm{Y}$, $A > 12$, exist. However, they are known to increase fairly uniformly with A and do not become more than a few percent of the (γ, p) or (γ, n) values for any nuclide

TABLE 1

REACTIONS RELEVANT TO LIGHT ELEMENT PHOTOEROSION

Reaction	$\langle\sigma\rangle$ in 10^{-27} cm^2	References
$^4He(\gamma, p)^3H$[a]	0.017	1
$^4He(\gamma, np)^2H$	0.0013	2
$^4He(\gamma, n)^3He$[a]	0.017	1
$^4He(\gamma, {}^2H)^2H$	5.5×10^{-5}	1
$^3He(\gamma, n)2p$	0.066	3
$^3He(\gamma, {}^2H)p$	0.103	4
$^2H(\gamma, p)n$	1.62	5, 6
$^7Li(\gamma, n)^6Li$	0.055	7
$^7Li(\gamma, p)^6He$	0.055	8
$^7Li(\gamma, {}^3H)^4He$	0.074	8
$^7Li(\gamma, d)^5He$	0.018	8
$^AX(\gamma, {}^2H)^{A-2}Y$[b]	0.002	9
$^{12}C(\gamma, p)^{11}B$	0.12	10
$^{12}C(\gamma, n)^{11}C$	0.040	11, 12

[a] Corrected for the yield from the $^4He(\gamma, np)^2H$ reaction.

[b] X refers to elements with masses between C and Fe, Y to the element with a charge one less than that of X.

REFERENCES.—(1) Arkatov *et al.* 1974; (2) Balestra *et al.* 1979; (3) Faul *et al.* 1981; (4) Ticcioni *et al.* 1973; (5) Birenbaum *et al.* 1985; (6) Evans 1955; (7) Ferdinande *et al.* 1977; (8) Junghans *et al.* 1979; (9) Bangert *et al.* 1976; (10) Kirichenko *et al.* 1978; (11) Ishkhanov *et al.* 1972; (12) Cook *et al.* 1966.

Chizhov *et al.* 1962). In view of the paucity of $(\gamma, {}^2H)$ data, the cross section for a nucleus intermediate between Fe and C, ^{25}Mg, was assumed to be typical. The ^2H production from the $(\gamma, {}^2H)$ reaction on $A > 12$ nuclides was then calculated using the summed abundances of all the nuclides between C and Fe. The ^2H yield from $(\gamma, {}^2H)$ reactions on $A > 12$ nuclides is thus quite uncertain, but it appears to contribute no more than a few percent of the total ^2H abundance, so adds little to its overall uncertainty.

The energy-averaged cross sections, $\langle\sigma\rangle$, are defined as

$$\langle\sigma\rangle = \int \sigma(E)E^{-2.7}\,dE \Big/ \int E^{-2.7}\,dE .$$

The rate equations to be solved, then, are

$$\begin{aligned} d[^3He]/dt &= [^4He]\phi\{\langle\sigma[^4He(\gamma, n)]\rangle + \langle\sigma[(^4He(\gamma, p)]\rangle\} \\ &\quad - [^3He]\phi\{\langle\sigma[^3He(\gamma, n)]\rangle + \langle\sigma[^3He(\gamma, p)]\rangle\} , \\ d[^2H]/dt &= [^3He]\phi\langle\sigma[^3He(\gamma, {}^2H)]\rangle + \phi\Sigma[i]\langle\sigma[i(\gamma, {}^2H)]\rangle \\ &\quad + [^4He]\phi\{2\langle\sigma[^4He(\gamma, {}^2H)]\rangle + \langle\sigma[^4He(\gamma, np)]\rangle\} \\ &\quad - [^2H]\phi\langle\sigma[^2H(\gamma, p)]\rangle ; \\ d[^7Li]/dt &= -[^7Li]\phi\{\langle\sigma[^7Li(\gamma, p)]\rangle + \langle\sigma[^7Li(\gamma, n)]\rangle \\ &\quad + \langle\sigma[^7Li(\gamma, {}^3H)]\rangle\} ; \end{aligned}$$

and

$$d[^{11}B]/dt = [^{12}C]\phi\{\langle\sigma[^{12}C(\gamma, n)]\rangle + \langle\sigma[^{12}C(\gamma, p)]\rangle\} .$$

The densities, e.g., $[^3He]$, are number densities. In solving these equations, $[^4He]$ was assumed to be constant at 0.08 of the total number of particles; while this is not strictly valid near the Galactic center (as $[^3He]$ can become the same order of magnitude in material subjected to intense—either for long times or at high flux—photoerosion), it is not badly violated. Note that some of the very small cross sections, e.g., that for $^4He(\gamma, d)$, are compensated for in the above equations by large abundances, e.g., $[^4He]$, and that there are no processes in photoerosion which make ^7Li, at least in appreciable quantities. Photoproduction of composite particles, even ^4He, is rare, so such processes are not expected to contribute an appreciable amount of ^7Li. Furthermore the instability of all mass 8 nuclides blocks production via single-nucleon photoemission from above, and deuteron emission from ^9Be is also not expected to contribute much since (Boyd and Ferland 1987) even for intense photoerosion, $[^9Be]$ is small. Similarly, although there are processes which destroy ^{11}B, they would not be expected to be significant while $[^{11}B]$ remains small. Thus photoerosion produces ^{11}B (Boyd and Ferland 1987).

If the photon flux ϕ is assumed to fall off with distance from the center of the Galaxy as r^{-2}, then these rate equations can be solved for all r, assuming initial abundances; we assumed the solar values (Cameron 1982). The solutions are shown in Figure 1, for assumed processing times of 10^9 yr at the NGC 4151 flux value; those solutions depend on the product of flux and processing time. The conclusions stated above are obvious from this graph; $[^3He]$ and $[^2H]$ increase as a result of photoerosion, especially close to the Galactic center (where ϕ is large), while $[^7Li]$ decreases, since it has no significant production processes.

Recapture of photoneutrons emitted from the various photonuclear reactions before they decay was omitted from the above analysis because it appears to be unimportant at the densities, $< 2 \times 10^{12}$ cm^{-3} (Gaskell and Sparke 1986), associated with the molecular clouds. At that density, neutron capture by photons appears to be just on the verge of becoming significant. However, our estimate shows that, at a cloud density of 10^{14} cm^{-3}, $p(n, \gamma)$ reactions would increase the deuterium abundance by an additional 20%, at least near the Galactic center. As the cloud density increases further, the percentage change due to this effect increases very little, but the enhancement moves to larger radius.

The ^3He abundance should be capable of providing information on the importance of photoerosion in our Galaxy. If all of the gas near the Galactic center was processed, then the material now in the clouds should have abundances for ^2H a factor of 60, and for ^3He a factor of 1250, times the solar values. The ^7Li abundance is decreased by many orders of magnitude. For ^2H and ^3He the overabundance factors with respect to the primordial abundances (Boesgard and Steigman 1985) are even larger; these are plausible enhancements for a weak AGN which has undergone photoerosion for several billion years, or a more intense one which has undergone photoerosion for a proportionally shorter time!

Furthermore, the gradient for $[^3He]$ near the Galactic center should indicate the extent to which mixing has occurred. While variations in $[^3He]$ have been observed (Bania, Rood, and Wilson 1987) in various Galactic locations, the detail necessary to determine the extent to which our Galaxy has been an AGN, and the extent to which the photoprocessed material near the center has been mixed, does not exist at present. ^3He is detected, via the 8.7 GHz line of $^3He^+$, with radio telescopes. The angular resolution required for such a measurement is the order of 1′, about that achievable with the largest radio telescopes presently available. However, production of that line requires ionized He, a requirement which may be incompatible with a medium which contains molecular clouds. But if some

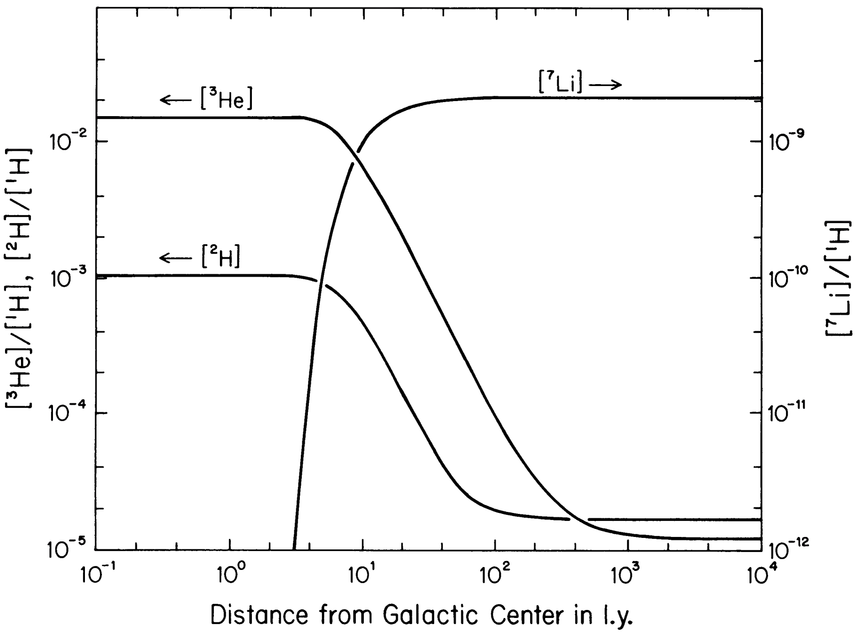

FIG. 1.—Abundances of ^{2}H, ^{3}He, and ^{7}Li as a function of distance from the Galactic center. The parameters assumed are explained in the text.

regions containing ionized He do exist near the Galactic center, the proposed experiment should be feasible.

If the B isotopic abundances near the Galactic center could be deduced, or if it could be assumed that the Galactic material became mixed in the lifetime of our Galaxy, the abundances of the B isotopes could be used to place a very tight upper limit on the extent to which our Galaxy could have existed as an AGN with parameters like those of NGC 4151. Unfortunately B lines are difficult to observe near the center of our Galaxy, and the requisite mixing is thought not to have occurred (Mihalas and Binney 1981). For ^{11}B, however, the enhancement near the Galactic center would be enormous, as, using the NGC 4151 parameters in the equation given above, [^{11}B] is found to exceed [^{1}H]! (In this case, the rate equation given above requires other terms, which would limit [^{11}B].) Since $[^{11}\mathrm{B}]/[^1\mathrm{H}] = 2.7 \times 10^{-10}$ (Cameron 1982) in the solar system, either the assumed (flux) × (time) for our Galaxy is very small, or the resulting material is poorly mixed. ^{11}B is generally thought to be made by spallation (Reeves *et al.* 1970). However, ^{10}B is thought to be made by the same process; the ratio $[^{11}\mathrm{B}]/[^{10}\mathrm{B}]$ predicted by cross section ratios is 2.4. The value observed in the cosmic-ray B isotope ratio, however, exceeds that ratio by almost a factor of 2 (Cameron 1982). If it is assumed that some mixing does occur, and that the excess ^{11}B is attributed completely to photoerosion, we can deduce an upper limit on the product of the photon flux, the photoerosion time, and the fraction of the galactic mass which is mixed η from the equation:

$$\text{Excess } [^{11}\mathrm{B}] = [^{12}\mathrm{C}]\phi\{\langle\sigma[^{12}\mathrm{C}(\gamma, n)]\rangle + \langle\sigma[^{12}\mathrm{C}(\gamma, p)]\rangle\}\eta t ,$$

since ^{11}C beta decays quickly into ^{11}B. Using solar abundances (Cameron 1982), we can deduce $\phi\eta t = 2 \times 10^{21}$ photons cm^{-2}, more than 11 orders of magnitude below that assumed for the results of Figure 1. Thus photoerosion could not have had much effect on the abundances of ^{2}H and ^{3}He in our Galaxy, except near the center, although it could be responsible for roughly 50% of our ^{11}B, even with very little Galactic mixing.

To check further on possible constraints on the flux we looked at the possible production by photoerosion of the very rare odd-odd nuclei ^{138}La and ^{180}Ta via ^{139}La(γ, n) and ^{181}Ta(γ, n) reactions [other reactions, e.g., (γ, pn) would be expected to add only small additional amounts]. For an integrated flux that produces ^{11}B at the observed level we found [^{138}La] down by a factor of 50 from its observed level and [^{180}Ta] down by at least a factor of 6 (the latter case is complicated by the nuclear effects which make the long-lived state isomeric). Thus photoerosion cannot easily explain the abundances of these shielded (from r-process and s-process production) nuclei unless significant destruction of the B produced by photoerosion has occurred.

Thus photoerosion is found to provide a mechanism for production of relatively large amounts of ^{3}He and ^{11}B near the Galactic center. While ^{11}B is difficult to detect in that region, measurement of the gradient of [^{3}He] at roughly the angular resolution of an arc minute does appear to be feasible and could provide a definitive test of the assertion that our Galaxy has operated as an AGN at some time in its past. The abundance of ^{2}H, while less enhanced by photoerosion than those of ^{11}B and ^{3}He, could provide similar information with similar spatial resolution. Furthermore, such measurements would provide limits on the product of the high energy photon flux from our Galactic center and the time over which that flux occurred.

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