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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.

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The abundances of the light elements ^2H, ^3He, ^4He, and ^7Li have been used to provide 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) has successfully explained 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 roughly 0.1 times that required to close the universe. While enormous effort has gone into extrapolating back in time to deduce the relationship between the primordial abundances and those presently observed, most such studies have assumed that any process which destroys ^3He or ^7Li will also destroy ^2H by an even greater amount, based on the relative fragility of the ^2H 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 et al., 1976) a ratio of $[^{11}B]/[^{10}B]$ 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 (AGN's), 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 AGN's 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 ^2H which would normally occur in regions of high photon density, resulting in a net production of ^2H. This feature could impinge on various models of big bang nucleosynthesis, e.g., the standard model mentioned above and those including 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 AGN's have undergone the scrutiny required 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. While this is clearly an extraordinary assumption, it 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 assumed 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/sec (Boyd and Ferland, 1987) at a distance of 2 l.d. from the galactic center. The region around a few l.d. 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.

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. Little information on cross sections of photon induced deuteron production reactions of the type ${}^{A}X(\gamma,{}^{2}H)^{A-2}Y$ exists; that for ${}^{25}Mg(\gamma,{}^{2}H)^{23}Na$ was assumed to be typical. This should produce a reasonable approximation, given the expected dependences of such reactions on A, reaction Q-value, and nuclear structure effects. The abundances of the nuclides between C and Fe were summed, and assumed to represent deuterium production from all the nuclides, with photoproduction cross section of ${}^{25}Mg(\gamma,{}^{2}H)$, in the calculations below.

The energy averaged cross sections used in the equations below, $<\sigma>$, are defined as

$$<\sigma> = \int \sigma(E)\ E^{-2.7}\ dE \ / \int E^{-2.7}\ dE.$$

The rate equations to be solved, then, are

$$d[{}^{3}He]/dt = [{}^{4}He]\phi\{<\sigma({}^{4}He(\gamma,n))> + <\sigma(({}^{4}He(\gamma,p))>\} - [{}^{3}He]\phi\{<\sigma({}^{3}He(\gamma,n))> + <\sigma({}^{3}He(\gamma,p))>\}.$$

$$d[{}^{2}H]/dt = [{}^{3}He]\phi<\sigma({}^{3}He(\gamma,{}^{2}H))> + \phi\Sigma[i]<\sigma(i(\gamma,{}^{2}H))> + 2[{}^{4}He]\phi<\sigma({}^{4}He(\gamma,{}^{2}H))> - [{}^{2}H]\phi<\sigma({}^{2}H(\gamma,p))>.$$

$$d[{}^{7}Li]/dt = -\ [{}^{7}Li]\phi\{<\sigma({}^{7}Li(\gamma,p))> + <\sigma({}^{7}Li(\gamma,n))> + <\sigma({}^{7}Li(\gamma,{}^{3}H))>\}.$$

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

The densities, e.g., $[{}^{3}He]$, are number densities. In solving these expressions, $[{}^{4}He]$ was assumed to be constant at 0.08 of the total number of particles; while this may not be strictly valid near the galactic center (as $[{}^{3}He]$ can become the same order of magnitude in material subjected to photoerosion for very long times), it is not badly violated any-where. 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, in this case, $[^4He]$. Note also 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 emission from above, and deuteron emission from ^9Be is also not expected to contribute much since, (Boyd and Ferland, 1987) even for long photoerosion times, $[^9Be]$ is small. Similarly, although there are processes which could destroy ^{11}B, they would not be expected to be significant as long as $[^{11}B]$ 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 Fig. 1, for assumed processing times of 10 billion years. 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.

Another effect, recapture of photoneutrons emitted from the various photonuclear reactions before they decay, has been omitted from the above analysis because, at the densities (Gaskell and Sparke, 1986) associated with the molecular clouds, $< 2 \times 10^{12}$ cm^{-3}, it does not appear to be important. At that density, neutron capture by protons appears to be just on the verge of becoming significant. It is decidedly nonthermal, as the

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neutrons scatter only a few times before they decay or are captured. Our estimate shows that, at a cloud density of 10^{14} cm^{-3}, p(n,γ) reactions would increase the deuterium abundance by an additional 20%, at least near the galactic center. As the cloud density increases, the percentage change due to this effect increases very little, but the enhancement moves to larger radius.

The ^{3}He abundance appears capable of providing information on the importance of photoerosion in our galaxy. Assuming that all of the gas within a few l.d. of the galactic center was processed, then the material in the clouds should have abundances for ^{2}H a factor of 60, and for ^{3}He a factor 1250 times the solar values. The ^{7}Li abundance is decreased by 5%. For ^{2}H and ^{3}He the overabundance factors with respect to the primordial abundances are 18 and 100; these are plausible enhancements for an AGN which has undergone intense photoerosion for several billion years!

Thus the gradient for [^{3}He] near the center of the galaxy should be capable of indicating the extent to which photoerosion has existed in our galaxy, and therefore the extent to which our galaxy has ever been an AGN. Such a measurement might also determine the extent to which mixing has occurred. While variations in [^{3}He] 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 does not exist at present. ^{3}He 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 minute of arc, roughly that achievable with the largest radio telescopes presently available. However, production of that line requires an ionized medium, a requirement which may be incompatible with a medium which contains molecular clouds. But, if some regions in which ionized He does occur exist near the galactic center, the proposed experiment should be feasible.

If the boron isotopic abundances near the galactic center could be deduced, or if it could be assumed that the galactic material became mixed in the present lifetime of our galaxy, the abundances of the boron 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 boron 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, however, $[^{11}B]/[^{1}H] = 2.7\times10^{-10}$ (Cameron, 1982) in the solar system, either the assumed (flux)x(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 $[^{11}B]/[^{10}B]$ predicted by cross section ratios is 2.4. The value observed in the cosmic ray boron 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:

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

since ^{11}C beta decays quickly into ^{11}B. Using the solar abundances of Cameron (1982), we can deduce that $\phi\eta t = 2\times10^{21}$ photons cm^{-2}. This is more than eleven orders of magnitude below that assumed for the results of Fig. 1. Thus photoerosion could not have had much of an effect on the abundances of ^{2}H and ^{3}He in our Galaxy, except near the galactic center, although it could be responsible for roughly 50% of our ^{11}B, even with an extremely small amount of galactic mixing.

To check furthur 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 contribute 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- and s-process production) nuclei unless significant destruction of the boron produced by photoerosion has occurred.

Thus photoerosion is found to provide a mechanmism 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. Furthermore, such a measurement would provide limits on the product of the high energy photon flux and the time over which that flux occurred.

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Table 1. Reactions Relevant to Light Element Photoerosion

Reaction	$\langle\sigma\rangle$ in $10^{-27}cm^2$	Reference
$^4He(\gamma,p)^3H$	.018	Arkatov et al.
$^4He(\gamma,np)^2H$	.0013	Balestra et al.
$^4He(\gamma,n)^3He$	.018	Arkatov et al.
$^4He(\gamma,^2H)^2H$	$5.5x10^{-5}$	Arkatov et al.
$^3He(\gamma,n)2p$	.066	Faul et al.
$^3He(\gamma,^2H)p$	.103	Ticcioni et al.
$^2H(\gamma,p)n$	1.62	Birenbaum et al., Evans
$^7Li(\gamma,n)^6Li$	.055	Ferdinande et al.
$^7Li(\gamma,p)^6He$	.055	Junghans et al.
$^7Li(\gamma,^3H)^4He$	.074	Junghans et al.
$^7Li(\gamma,d)^5He$	.018	Junghans et al.
$^AX(\gamma,^2H)^{A-2}Y*$	.002	Bangert et al.
$^{12}C(\gamma,p)^{11}B$	.12	Kirichenko et al.
$^{12}C(\gamma,n)^{11}C$	.040	Ishkhanov et al., Cook et al.

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

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

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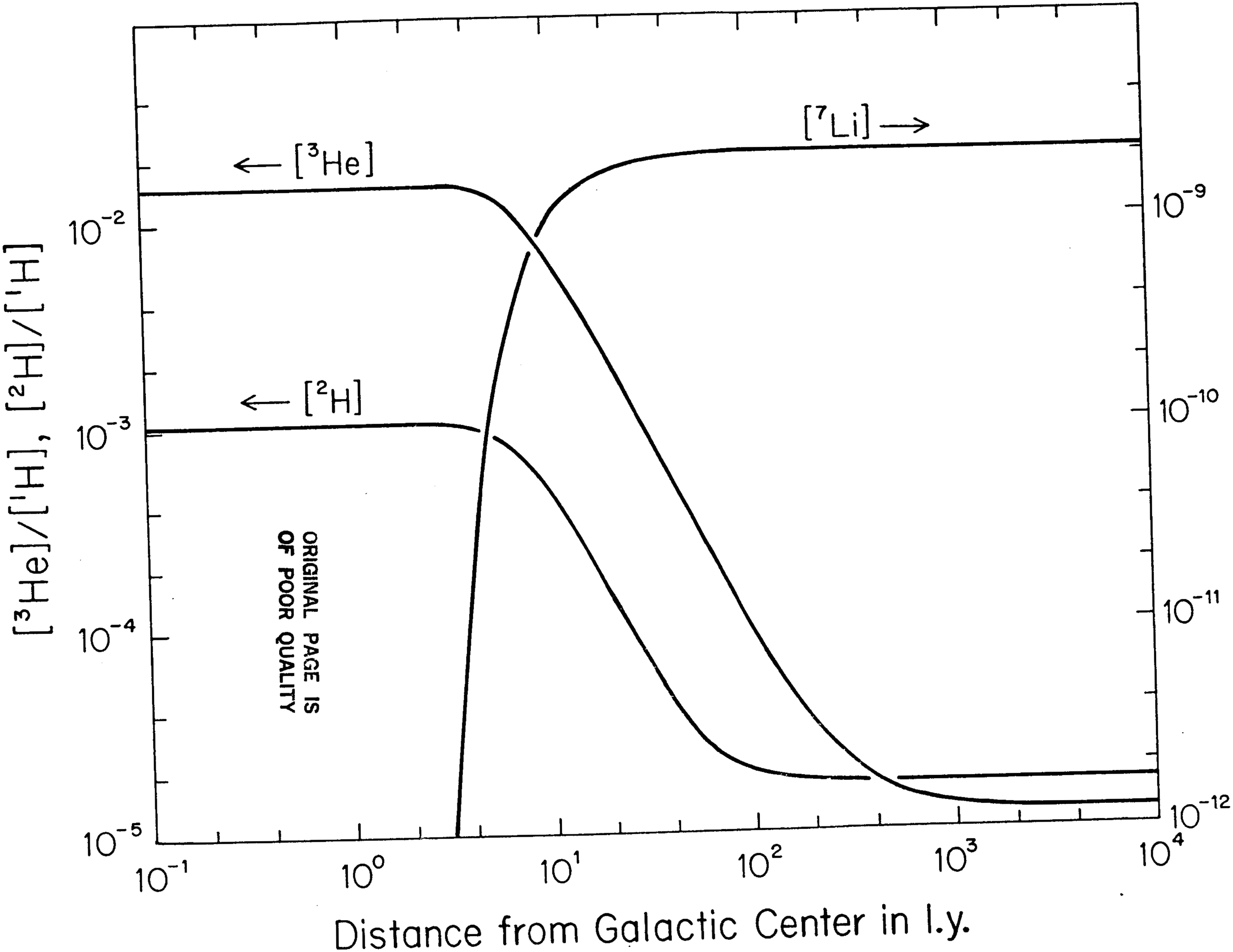
Figure caption: Abundances of ^{2}H, ^{3}He, and ^{7}Li as a function of distance from the galactic center. The parameters assumed are explained in the text.



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