

Production of ^2H , ^3He , and ^7Li from Interactions Between Jets and Clouds

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ABSTRACT

The interactions between jets of high-energy nuclei and nuclei of the surrounding medium are studied. Such interactions could be initiated by jets from active galactic nuclei interacting with surrounding cool clouds. The resulting nuclear interactions are found to produce copious amounts of ^2H and ^3He from the ^4He nuclei. These results suggest that jets of particles from quasars could have produced anomalously high abundances in surrounding clouds of some of the nuclides usually thought to characterize big bang nucleosynthesis, specifically, the ^2H seen in absorption spectra.

Subject headings: galaxies: jets—nuclear reactions, nucleosynthesis, abundances

The abundances of the nuclides ^2H and ^3He have long provided signatures of big bang nucleosynthesis (Hata et al. 1995, Copi, Schramm, and Turner 1995). In recent years, absorption lines from clouds along the line of sight from a quasar to earth have been used to determine the primordial ^2H abundance (Burles and Tytler 1998, Burles and Tytler 1999, Tytler and Burles 1997, Molaro et al. 1999, Kirkman et al. 2000). The values obtained from these studies were found to be consistent with the traditional value. However, the same technique has also resulted in some “primordial” ^2H abundance values (Songaila et al. 1994, Carswell et al. 1994, Rugers and Hogan 1996) that were up to an order of magnitude larger. Subsequent reanalysis of these systems has suggested that the high ^2H abundances do not represent the primordial values, (Burles et al. 1999), but the issue is not completely resolved (Tosi et al. 1998). The question of whether or not the high ^2H abundance is primordial has been addressed from the standpoint of primordial inhomogeneities in the baryon-to-photon ratio, with the conclusion being that if such inhomogeneities are not responsible for the observed ^2H abundance, then processes occurring after the initial primordial nucleosynthesis

must be responsible. Two such processes are stochastic and anomalous chemical evolution in Lyman limit systems (Jedamzik & Fuller 1997). Photoerosion reactions, induced by photons from, e.g., an accreting black hole, on atomic nuclei have also been suggested as a possible source for the production of light elements (Boyd et al. 1989). Another proposed source of processing is the photon flux from accreting black holes that might have been created from the collapse of an early generation of massive stars formed shortly after decoupling (Gnedin & Ostriker 1992, Gnedin et al. 1995). However, this model has difficulty in predicting abundances that match observation (Balbes et al. 1996). In this Letter we show that spallation production of these light nuclides would be the *inevitable* result of jets of high-energy nuclei hitting nuclei in the surrounding medium contained, e.g., in cool clouds, and that such interactions could readily produce enough ^2H in the cloud to explain the high ^2H observation. Since both required entities are expected in many quasars, high ^2H abundances might be occasionally expected. However, a range of abundances from primordial to roughly the high values could be produced by this mechanism.

We have studied the production of ^2H and ^3He from interactions between jets and clouds, both entities commonly associated with quasars and AGNs. The ^2H and ^3He would be produced from interactions between ^1H and ^4He from a jet interacting with ^1H and ^4He (assumed primordial abundances) in ambient gas. A localized buildup of ^2H and ^3He would result from these interactions and, as we show below, could readily lead to ^2H and ^3H abundances more than an order of magnitude larger than the “low” primordial ^2H abundance. Such abundances might then produce the observed high ^2H absorption features from very distant quasars, so could provide a natural explanation for the origin of the “high” ^2H abundance.

We have assumed parameters for the jets and clouds that are typical of those seen in AGNs. Typical sizes of clouds around active galactic nuclei are 400 solar radii, with typical

densities of 10^{11} particles cm^{-3} (Peterson 1997); this corresponds to roughly a $10^{-6} M_{\odot}$ object. For convenience, we have assumed the clouds to be cylinders with equal diameters and thicknesses, and with the axis of symmetry in the direction of the jet. This is about what is required to stop 100 MeV protons, or 400 MeV ^4He nuclei, so it is appropriate to assume that such clouds would stop the high-energy nuclei. Since there are thought to be many clouds ($\sim 10^5$) about each active galactic nucleus and, presumably, quasar, any jet might well process material in many clouds. For AGN jets, $1 M_{\odot} \text{y}^{-1}$ is a plausible value for the jet output (although this doesn't really matter; the product of the jet intensity that intersects a cloud and the time during which they interact is what matters), and their breadth would be expected to exceed the size of a typical cloud by a large factor. Typical jet radii at the cloud are about 0.01 - 0.1pc (Lobanov (1997), Peterson 1997), so the fraction of mass actually incident on the cloud is proportional to the fraction of cloud and jet cross sectional areas. Therefore, we have assumed a cloud of $10^{-6} M_{\odot}$ is bombarded by a jet of 100 MeV protons and 400 MeV ^4He nuclei at a rate of $10^{-3} M_{\odot} \text{year}^{-1}$ (although only the total flux matters).

Production by spallation of ^2H and ^3He was examined by means of a computer code which determines the yields of various spallation reactions caused by collisions between incident high-energy nuclei and the nuclei at rest within a stopping medium. As a high-energy projectile enters the stopping medium and is slowed by electronic energy loss, it may undergo one of several nuclear reactions in a collision with a target nucleus at rest. The code tracks the ^4He particles through the cloud, calculating the fraction of incident particles that undergo each possible reaction that destroys incident nuclides and creates other nuclei as reaction products, as well as those that come to rest in the stopping medium. The reaction products are also tracked through subsequent possible reactions or to their being deposited in the stopping medium. The incident material and the reaction products are assumed to be well mixed in the stopping medium so that, given that the total jet mass

is assumed to be less than 10% of that of the stopping medium, the cloud nuclei are not significantly depleted or diluted.

Spallation cross sections were taken from the literature when available (Meyer 1972); the reactions included in the code are listed in Table 1. However, a paucity of data for many of the reactions necessitated calculations of some cross sections. It appears (Rogers et al. 1970) that the direct reaction mechanism is primarily responsible for the reactions



Thus the secondary particle energy distributions of the outgoing ${}^3\text{He}$ and ${}^2\text{H}$ particles were calculated by the direct reaction code DWUCK (Kunz). Such calculations require specification of the nuclear optical potential parameters. Those for reactions involving protons follow the general parametrization of Menet et al. (1971) as shown in Perey and Perey (1976). While this parametrization was based on a study of lower energy protons (30 to 60 MeV) than some of those with which we are concerned, the fit to higher energy data is quite similar to parameter sets determined from higher energy data (Perey and Perey, 1976, Schwandt et al. 1982). For reactions involving deuterons, the parametrization of Perey and Perey (1976) was also employed, but with the spin-orbit parameters of Lohr et al. (1974) added on. The use of these parameters gave results that closely matched the experimental results of Rogers et al. (1969). Potential parameters for α -particles followed Perey and Perey (1976).

Little information exists for the three-body final state reactions, although one study (Brinkmüller et al. 1990) indicates that the three-body final states tend to smear out the structure seen in the energy distributions of the two-body final state reactions. Some

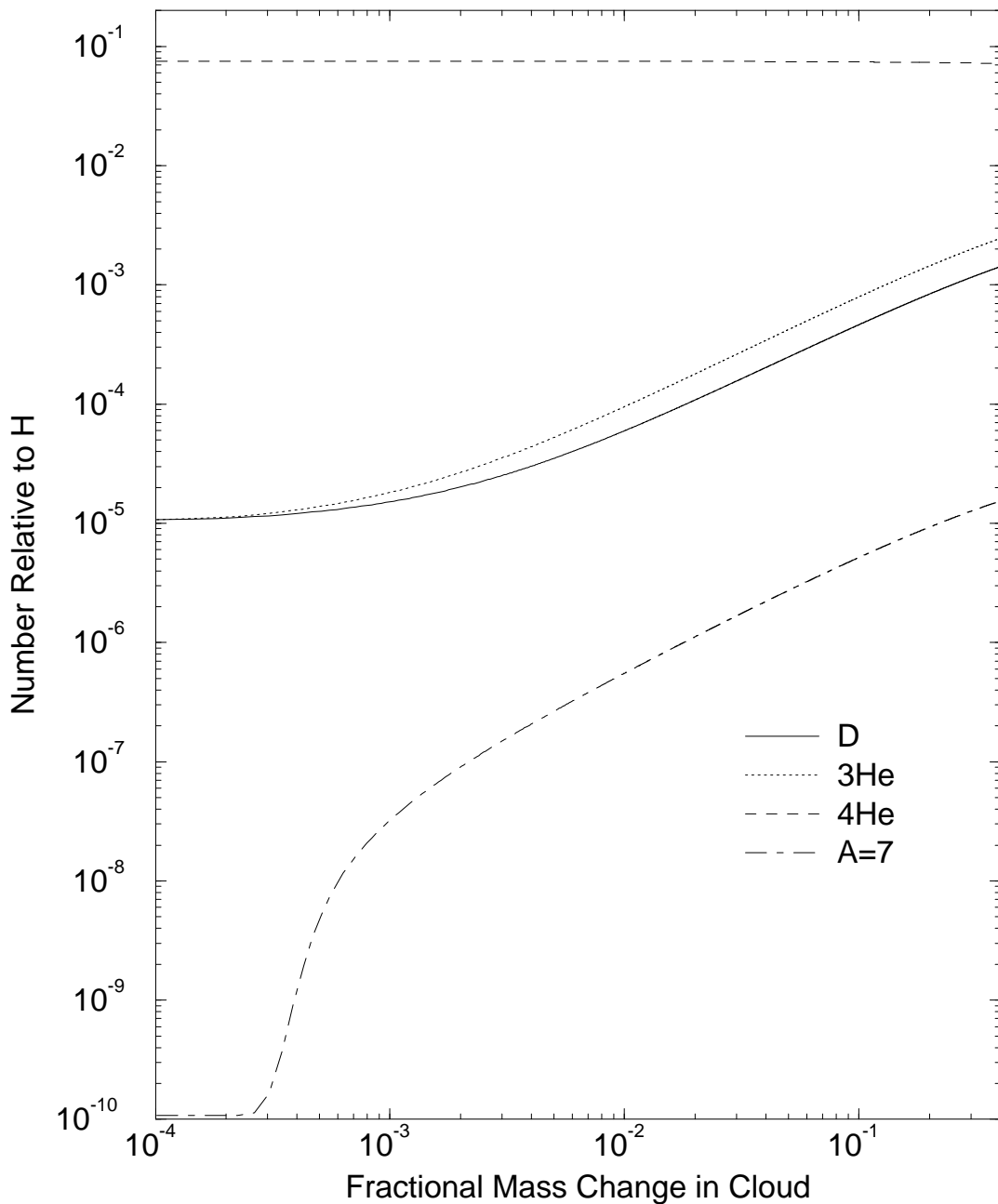


Fig. 1.— The final abundances of D, ³He, ³H, and ⁴He due to the spallation of ⁴He into a stopping medium of primordial composition. For this figure the initial jet energy is assumed to be 400A MeV.

peaking toward the higher energies is suggested by the one existing data set. Thus we assumed two possibilities as extreme cases: (a) one in which the distributions of the reaction products were constant with energy, and (b) one in which the distributions were enhanced by a factor of two for the particles in the top quarter of the energy distributions. This change produced effects in our results only at the 1% level; the highest energy component is small. However, this procedure did allow a test of the sensitivity of the results to the shape of these poorly known cross sections. The magnitudes of the cross sections for the three-body final states are unknown. Thus we assumed they scaled with energy as does the $^1\text{H}(^4\text{He},^3\text{He})\text{d}$ cross section; their ratio was then fixed at the one energy at which the three-body final state reaction, $^1\text{H}(^4\text{He},\text{n p})^3\text{He}$, was studied (Brinkmüller et al. 1990). Data for the interaction of ^4He with ^4He are in similarly short supply. Thus we simply assumed that, for such interactions, the yields would be three times the values for ^4He interacting with protons at the same center of mass energy, as recommended by Meyer (1972).

The production of mass 7 elements is included via the reaction $^4\text{He}(^4\text{He},\text{n/p})^7\text{Be/Li}$, and the inverse reaction is also included, with cross-sections given by Mercer et al. (1997) and Abramovich et al. (1984). Recent studies on mass 7 nuclei give total reaction cross sections for the proton interactions with ^7Li and ^7Be (Carlson et al. 1985), and excitation above the particle emission threshold is obtained by subtracting the inelastic scattering cross sections to the first excited states of these nuclei (Locard et al. (1967)). This is appropriate because excitation of states higher lying than the first excited state in either ^7Be or ^7Li results in destruction of the nucleus.

Figure shows the results of one set of our calculations. The results are presented there in a way that allows that graph to be used as a universal predictor that depends only on the cross sections used in the calculations, i.e., the abundances of the light nuclides are

given as a function of the fraction of the total mass of the cloud $M_{deposited}$ that was added by the jet. The value of $M_{deposited}$ is given by

$$M_{deposited} = (dM/dt)_{jet} t f_{overlap} \quad (4)$$

where $(dM/dt)_{jet}$ is the rate of mass output within the jet, t is the time during which the jet interacted with the cloud, and $f_{overlap}$ is the fraction of the jet that actually interacts with the cloud. As can be seen from Fig. 1, when the mass of the cloud has increased by 1% from the matter added by the jet, the abundances of ^3He (which includes that of ^3H) and ^2H have already increased appreciably, roughly by a factor of four, from those normally associated with primordial nucleosynthesis. Furthermore, their abundances when 10% of the mass of the cloud has been added are roughly a factor of 30 above their primordial values. Their abundances for this jet energy level off gradually as additional mass is added, due to (1) our assumption that the density of the cloud remains constant, i.e., the volume of the cloud increases with the amount of mass transferred to it by the jet (and the cloud is well mixed), and (2) the fact that the fraction of ^4He nuclei that are destroyed depends only on the energy. The values for even larger mass depositions can be as much as a factor of five higher than those achieved at 10% added mass, although amounts of added mass to the cloud in excess of that might well destroy the cloud.

The parameters of the jet and the cloud assumed for this calculation are typical of actual systems, as noted above. The cloud mass assumed was $10^{-5} M_{\odot}$, the jet output was $1 M_{\odot} \text{ y}^{-1}$, and $f_{overlap}$ was taken to be 10^{-3} . Therefore, the mass deposited into the cloud was $0.001 M_{\odot} \text{ y}^{-1}$. In the case of this mass flux, the cloud mass will increase considerably in a relatively short amount of time. While this is probably an unrealistically short time scale for a physical situation, the relevant parameter is the ratio of the transferred mass to the total mass of the cloud. The context in which the actual time scale might matter would be if reactions occurred on time scales that were shorter than or the order of the β -decay

half-lives of the unstable nuclei created: ${}^7\text{Be}$ and ${}^3\text{H}$. Assuming, though that those nuclides always decay, rather than interact again, they will merely contribute to the abundances of ${}^7\text{Li}$ and ${}^3\text{He}$. Thus the abundances of these unstable nuclides are simply summed with those of their stable isobars in Figure 1.

That Figure shows how the ${}^2\text{H}$ abundances increases with the amount of jet mass that interacts with the cloud. Also seen to increase are the abundances of ${}^3\text{He}$ and ${}^7\text{Li}$, in all cases well above their primordial values. Thus the jet-cloud interaction mechanism is clearly capable of producing large abundances of ${}^2\text{H}$, ${}^3\text{He}$, and ${}^7\text{Li}$ even when the nuclei of the jet and the reaction products from the reactions it precipitates are admixed into a considerably larger cloud mass.

The energy chosen for the case for which the results are shown in Fig. 1 was selected to be well above the thresholds for producing the ${}^7\text{Li}$, ${}^3\text{He}$, ${}^3\text{H}$, and ${}^2\text{H}$ reaction products. As might be expected, even larger ${}^2\text{H}$, ${}^3\text{He}$ and ${}^7\text{Li}$ abundances are observed at higher energies. However, the increases with energy are not large, as the fragile reaction products made at the higher initial energies tend to be destroyed. At 100A MeV 8% of the high-energy ${}^4\text{He}$ will be spalled into lighter nuclides, while at 500A MeV the fraction increases to 26%. However, increases in energy do not necessarily produce more ${}^3\text{He}$ and ${}^2\text{H}$. The production of ${}^2\text{H}$ and ${}^3\text{He}$ peaks at around 500A MeV, as those nuclei, if produced at energies above 500A MeV, will essentially all be destroyed by subsequent spallation reactions. We have further assumed that the high energy particles stop in the medium in which the interactions that produce the ${}^2\text{H}$ and ${}^3\text{He}$ occur. This is clearly not a critical assumption, although if the medium were thin enough for the high-energy particles to emerge with energies above the reaction thresholds, then the resulting ${}^2\text{H}$ and ${}^3\text{He}$ abundances would decrease accordingly.

Could the clouds that are associated with AGNs or quasars be identified as the intergalactic clouds that produce the absorption lines? A fascinating consequence could

exist within our own galaxy, the core of which has been observed to contain much higher deuterium abundances than expected (Lubowich et al. 2000). While primordial infall is a suggested possibility, the observations are consistent with the possibility that the galactic center resulted from jet-cloud interactions in an AGN. The clouds in which we have assumed the processing of ^4He to ^2H and ^3He are close to the central engine of the quasar and are at a higher density than those in which the absorption occurs. However, the jets that we have assumed to interact with the clouds would impart momentum to the clouds, which would be loosely bound to the quasar. Although the jet-cloud interaction is complex (see, e.g., Wang et al. 2000), it does seem plausible that the clouds in which the jet-cloud interactions occur could evolve into those in which the ^2H absorption occurs. Indeed, as noted above, a spread in the values of the ^2H abundance would be expected, and this is not inconsistent with that observed (see references in the introductory paragraph) in distant absorption clouds. Note, though, that if the jet-cloud mechanism is found to be important, the values observed for ^2H will provide a lower limit on the primordial deuterium abundance; averaging those values would lead to too high a “primordial” abundance.

Finally, ^7Li is predicted to have a very large abundance compared to either solar system or primordial abundances. This overabundance would be consistent with the enhanced Li abundance inferred in the galactic center (Lubowich et al. 1998). Note that, if the jet-cloud interaction is the explanation, this ^7Li enhancement must accompany the enhanced ^2H abundance; the two are produced concurrently by interactions within the same primordial material. Thus the dual enhancement of ^2H and ^7Li constitutes a test of this model. Mixing subsequent to the jet-cloud interaction with material processed in stars would distort the ratio of those abundances from those predicted here. Furthermore, the actual ratio of the abundances depends on the energy of the particles in the jet; the abundance ratio of ^2H to ^7Li if the α -particles in the jet have 200 MeV of energy is 25, whereas it is 500 at 1000 MeV. Even with an uncertain amount of mixing and a large uncertainty in the energy of

the particles in the jet, though, the qualitative feature of a large dual enhancement would be preserved.

In summary, the results of calculations describing the interactions between nuclei in intersecting jets and clouds has shown that large abundances of ^2H , ^3He , and ^7Li can be produced therefrom. This might provide an explanation for the observed anomalously high “primordial” ^2H abundance. This mechanism also provides a way for *producing* ^2H , normally thought to be only destroyed by galactic chemical evolution. Although prediction of the specific enhancements of ^2H , ^3He , and ^7Li that could result in clouds is complicated by the several parameters needed to fully define the situation, it is clear that the spallation mechanism can produce copious quantities of these nuclides. The possibilities of such production might also be expanded to the realm of higher-metallicity regions. Many QSO spectra seem to indicate considerable abundances of the CNO elements (Hamann & Ferland 1999). Future work will concentrate on the jet interactions with clouds enhanced in these heavier elements.

We note that, if the spallation production of ^2H and ^3He is common, it should be relatively easy to find situations in which these nuclides have been produced by searching for other absorption lines from quasars. This mechanism would be expected to produce a wide range of values of the observed ^2H abundance, ranging from the true “primordial” value to the maximum that can be produced by this mechanism, apparently even greater than the highest deuterium value yet observed. Such observations could constitute a confirmation of the jet-cloud spallation model.

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Table 1: Spallation Reactions
between ${}^4\text{He}$ and ${}^1\text{H}$ on secondary projectiles

$p({}^4\text{He},pn){}^3\text{He}$	$p(d,pn)p$
$p({}^4\text{He},2p){}^3\text{H}$	$p({}^3\text{He},dp)p$
$p({}^4\text{He},d){}^3\text{He}$	$p({}^3\text{He},ppn)p$
$p({}^4\text{He},p)2d$	$p({}^3\text{H},dp)p$
$p({}^4\text{He},2p)dn$	$p({}^3\text{H},pnn)p$
$p({}^4\text{He},2n)3p$	${}^7\text{Li}(p,{}^4\text{He}){}^4\text{He}$
