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NEUTRINO PRODUCTION OF DEUTERIUM IN SUPERMASSIVE STARS AND POSSIBLE IMPLICATIONS FOR DEUTERIUM DETECTIONS IN LYMAN-LIMIT SYSTEMS

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ABSTRACT

We describe how thermally produced antielectron neutrinos ($\bar{\nu}_e$) from the homologously collapsing core of a supermassive star ($M \gtrsim 5 \times 10^4 M_\odot$) can lead to significant deuterium enrichment in the ejected envelope of such a star. Deuterium-enriched material at high redshift might then serve as a clue to the existence of pregalactic supermassive stars. Conceivably, the ejected deuterium-enriched material could intercept the line of sight to a distant QSO and mimic a Lyman limit absorber. In such a case, the deuterium abundance inferred from absorption lines might not reflect the true primordial abundance of deuterium. We discuss relevant theoretical uncertainties in supermassive star physics as well as potential observational signatures in Lyα absorber clouds for processing by stars of this kind.

Subject headings: cosmology: observations — cosmology: theory — elementary particles — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

In this Letter we assess the prospects for deuterium synthesis resulting from $\bar{\nu}_e$-induced neutron production in supermassive stars ($M \gtrsim 5 \times 10^4 M_\odot$—these objects become dynamically unstable as a result of the general relativistic instability). We will show that this process cannot account for the observed interstellar or solar system deuterium abundance. However, it might result in *local* enrichment of deuterium above its primordial value in the ejecta from a collapsed supermassive star. This might give a telltale sign of the existence and evolution history of pregalactic supermassive stars—as yet there is no direct evidence for these objects ever having been extant in the universe, although it has been argued that their formation may be an inevitable consequence of the evolution of dense star clusters and perhaps ultra-low metallicity environments in the early universe (Hoyle & Fowler 1963; Begelman & Rees 1978; Fuller, Woosley, & Weaver 1986, hereafter FWW; Bond, Arnett, & Carr 1984; McLaughlin & Fuller 1996).

If such deuterium-enriched ejecta at high redshift intercept a line of sight to a more distant QSO, then it could mimic a Lyman limit absorber. Measurement of isotope-shifted hydrogen absorption lines in such a system may then lead to an erroneous estimate of the primordial deuterium abundance (D/H) and, hence, an incorrect inference of the fraction of the closure density contributed by baryons, Ω_b. Future indisputable observations of significantly discordant D/H values among different Lyman limit systems, or very high values of this quantity, may be a signal for the existence of pregalactic supermassive stars. Confirmation of such a conjecture would depend on other evidence of supermassive star processing (FWW): nucleosynthesis products of hot hydrogen burning (the *rp*-process; Wallace & Woosley 1981), greatly enhanced helium abundances, or effects of large black holes.

Deuterium is very fragile in stars. Thus to search for the primordial value of D/H one has to look for gas clouds unprocessed by stars. Low-metallicity Lyα absorbers at high redshifts are thought to be such primordial clouds with little stellar processing (see Jedamzik & Fuller 1997). So far, measurements derived from three Lyman-limit absorption systems are available. One indicates a high value with D/H = $1.9(\pm 0.5) \times 10^{-4}$ (Songaila et al. 1994; Rugers & Hogan 1996; see, however, Tytler, Burles, & Kirkman 1996), and two yield low values with D/H = $2.3(\pm 0.3 \pm 0.3) \times 10^{-5}$ and $2.5(\pm 0.5 \pm 0.4) \times 10^{-5}$, respectively (Tytler & Burles 1997; Tytler, Fan, & Burles 1996). The implications of these measurements for primordial nucleosynthesis and the value of Ω_b have been discussed extensively (Cardall & Fuller 1996; Hata et al. 1997; Jedamzik & Fuller 1997; Copi, Olive, & Schramm 1996). One may be left with an uneasy feeling regarding how representative the three systems are of Lyman-limit systems in general. By necessity only systems with very narrow lines can show the sought-after isotope shift, and only systems with simple line profiles can minimize the chance of blending. Clearly these systems comprise a small fraction of the Lyman-limit systems along the lines of sight to bright QSOs.

The great bulk of deuterium in the universe is generated by freezeout from nuclear statistical equilibrium at high entropy in big bang nucleosynthesis (Wagoner, Fowler, & Hoyle 1967). It has been argued effectively that the bulk of the deuterium cannot be synthesized through cosmic-ray spallation or photodisintegration of nuclei (e.g., Epstein, Lattimer, & Schramm 1976; Sigl et al. 1995).

There are two characteristics of the deuteron which make its synthesis problematic: (1) it is the most fragile nucleus, with a binding energy of only 2.2 MeV; (2) it requires free neutrons. It is not easy to obtain free neutrons in astrophysical environments, and, to complicate matters, neutrons are unstable. They can only be "spalled" from bound nuclei, or produced directly via the weak interaction. The former production channel is difficult because neutrons are bound in nuclei by ~8 MeV, while the latter channel is problematic because weak interactions are inherently slow. Having somehow produced a free neutron, significant synthesis of deuterons then requires that the $n(p,\gamma)$ D rate be fast compared to the free neutron decay rate and the local material/thermodynamic expansion timescale, while the primary deuteron destruction process, $D(p,\gamma)^3He$, is slow compared to the local material/thermodynamic expansion timescale. Supermassive stars come close to satisfying these requirements since they are low baryon density, relatively cool, high-entropy configurations, in which the $n(p,\gamma)\,\mathrm{D}$ rate is relatively fast and the $\mathrm{D}(p,\gamma)^3\mathrm{He}$ rate is relatively slow. The free neutrons, in this case, are produced by intense neutrino fluxes released during the collapse of supermassive stars via the weak reaction $\bar{\nu}_e + p \rightarrow n + e^+$.

The crux issue in this scenario for deuterium production hinges on whether *any* material in these stars can be ejected from regions where all the requirements to yield significant D/H enrichment are satisfied. Indeed, Woosley (1977) suggested that something like this process could account for all of the deuterium in the universe. Although we will argue that this is not possible given our current understanding of how supermassive stars evolve (FWW), it may still lead to significant local deuterium abundance enrichments, to as high as $\mathrm{D/H} \approx 10^{-4}$. We also show that the possibility that supermassive star ejecta form a "Lyman-limit system" is consistent with the characteristics of the currently observed Lyα absorption systems from which D/H values have been measured. We then discuss how to eliminate this possibility by further observations.

2. DEUTERIUM ENRICHMENT IN THE ENVELOPES OF SUPERMASSIVE STARS

In this section we will describe how D/H can be enhanced in some regions of a supermassive star via this three-step scenario:

1. The star collapses, and, near the point where the homologously collapsing core becomes a black hole, a fraction of the gravitational binding energy is radiated as thermally produced $\nu\bar{\nu}$ pairs.
2. The process $\bar{\nu}_e + p \rightarrow n + e^+$ creates free neutrons further out in regions of the star where material ejection is possible.
3. These neutrons undergo $n(p,\gamma)\,\mathrm{D}$ on a timescale short compared to the material expansion timescale and the neutron decay lifetime, yet the lifetime of the deuteron against destruction via $\mathrm{D}(p,\gamma)^3\mathrm{He}$ is long compared to the disassembly time (or inverse expansion rate) of this region of the star.

Leaving aside the thorny and unresolved issue of how a supermassive star could be formed, it is instructive to review the simple structure and evolution of nonrotating, primordial composition supermassive stars (FWW). These stars are radiation dominated, with essentially all the pressure support coming from photons, while nearly all the mass-energy in the star is contributed by baryon rest mass. These stars will have an adiabatic index $\Gamma_1 \approx 4/3$, will be nearly constant entropy, fully convective configurations, and as a result will be very accurately described as an index $n = 3$ Newtonian polytrope. Such a configuration will have close to zero total (internal plus Newtonian gravitational) binding energy and will be "trembling on the verge of instability"as outlined by Fowler (1964) and Iben (1963). In addition, this configuration will be radiating at the photon Eddington limit. As a result, the star will resemble an oversized Wolf-Rayet star and will be accompanied by continual and significant mass loss during its lifetime. This lifetime will be quite short, however, as the star will quasi-statically contract as it radiates away entropy. This will continue until the central density reaches a critical value, beyond which general relativistic effects ensure that the star becomes dynamically unstable. This instability point is roughly coincident with the onset of hydrogen burning for stars with masses $\sim 10^5\ M_\odot$. The subsequent fate of the star depends on a number of factors, principally composition, rotation, and magnetic pressure. Explosion or collapse to a black hole depends on how rapidly thermal energy can be added to the system through the competition between hot hydrogen burning, on the one hand, and thermal neutrino losses and the buildup of infall kinetic energy, on the other. In general, collapse to a black hole is probably inevitable for a zero-metallicity, nonrotating initial configuration (FWW).

However, there is a generic feature of this collapse which serves to isolate an outer region of the star from a "homologous core" which will plunge through the event horizon as a unit. Initially the entire star will collapse homologously, but as pressure is relatively reduced in the center by thermal neutrino emission, only an inner part of the star can continue to collapse homologously (Goldreich & Weber 1980; FWW). The boundary of this homologous core (as well as the mass enclosed) depends on the entropy per baryon, which in turn depends on the history of nuclear burning–driven entropy increase and neutrino loss–driven entropy decrease (FWW; Fuller & Shi 1997). Material outside of this core could be subject to ejection resulting from neutrino heating (Fuller & Shi 1997), and/or hot *rp*-process nuclear burning–driven convection combined with rotation and MHD effects (see Ozernoi & Usov 1971; Fowler 1966). Our work here is meant to suggest that detailed multidimensional numerical modeling of these scenarios merits serious attention.

Prodigious thermal neutrino losses will accompany the collapse of the homologous core (FWW). The peak neutrino–pair production rate will come near the point where the homologous core of mass M^{HC} approaches its Schwarzschild radius, $r_{\mathrm{S}} \approx 3 \times 10^5\ \mathrm{cm}\ (M^{\mathrm{HC}}/M_\odot)$, where the average density is $\bar{\rho}_{\mathrm{S}} \approx 1.8 \times 10^{16}\ \mathrm{g\ cm^{-3}}\ (M^{\mathrm{HC}}/M_\odot)^{-2}$. Crudely, the Newtonian gravitational binding energy at this point is $E_G^{\max} \approx 0.5 M^{\mathrm{HC}} c^2 \approx 10^{54}\ \mathrm{ergs}\ (M^{\mathrm{HC}}/M_\odot)$, while the free-fall timescale is $t_{\mathrm{S}} \approx 3 \times 10^{-5}\ \mathrm{s}\ (M^{\mathrm{HC}}/M_\odot)$.

Not all of the gravitational binding energy will be carried away by neutrinos. A fraction of the binding energy could reside in infall kinetic energy and thermal energy, be dissipated in magnetic modes, or be "stored"in rotational kinetic energy. In addition, neutrinos radiated from the core will be gravitationally redshifted. We designate the fraction of the binding energy radiated by neutrinos by f_E. This quantity f_E will be a significant fraction of unity if neutrinos are not trapped in the homologous core as a result of their mean free path becoming short compared to the core radius. (Fuller & Shi 1997 find that such trapping is unlikely except very near the black hole formation point for stars with initial masses above $M \gtrsim 10^5\ M_\odot$.)

During the collapse the temperature will be $T_9 \equiv T/10^9\ \mathrm{K} \approx 0.67(5.5/g)^{1/3} S_{100}^{1/3} \rho_3^{1/3}$, where S_{100} is entropy per baryon in units of 10^2 times Boltzmann's constant, ρ_3 is the density in $10^3\ \mathrm{g\ cm^{-3}}$, and g is the statistical weight in relativistic particles ($g \approx 2$ and $g \approx 11/2$ for $T_9 \lesssim 1$ and $T_9 \gtrsim 1$, respectively). S_{100} is typically between 1 to 10. Near the endpoint of collapse, the core temperature will be of order $T_9^{\mathrm{HC}} \sim 11.7(M_5^{\mathrm{HC}})^{-1/2}$, where M_5^{HC} is the homologous core mass in units of $10^5\ M_\odot$ at the blackhole formation point. Allowing for entropy loss by thermal neutrino emission and including a fair amount of angular momentum centrifugal support for M_5^{HC} could be about 1 order of magnitude smaller than the initial stellar mass (Fuller & Shi 1997). This implies that typical temperatures will be $T_9 \sim 10$–20 at the collapse endpoint for initial stellar configurations with $1 \lesssim M_5 \lesssim 10$. For $T_9 \sim 10$–20 the average energy of neutrinos produced as pairs in $e^{\pm}$ annihilation will be (see Schinder et al. 1987; Itoh et al. 1989) $\langle E_\nu \rangle \sim 6$–12 MeV. The neutrino energy will suffer an undetermined gravitational redshift of order 1, but for simplicity we absorb the redshift into the factor f_E.

The probability that the process $\bar{\nu}_e + p \rightarrow n + e^+$ converts protons at radius r into neutrons is

$$P \approx \frac{E_G^{\max} f_E}{\langle E_\nu \rangle} \left(\frac{1}{4\pi r^2} \right) \left(\frac{n_{\bar{\nu}_e}}{\sum_i n_{\nu_i}} \right) \langle \sigma(E_\nu) \rangle . \qquad (1)$$

The third term in this equation is the fraction of neutrinos which are $\bar{\nu}_e$ and is typically about 1/3. The cross section for $\bar{\nu}_e$ absorption on protons is $\sigma(E_\nu) \approx 10^{-43}\ \mathrm{cm}^2 (E_\nu/\mathrm{MeV})^2$ when $E_\nu \gg 1$ MeV. Therefore,

$$P \approx 1.5 \times 10^{-5} f_E M_5^{\rm HC} \left(\frac{\langle E_\nu \rangle}{10\ \mathrm{MeV}} \right) \left(\frac{3 n_{\bar{\nu}_e}}{\sum_i n_{\nu_i}} \right) \left(\frac{10^{13}\ \mathrm{cm}}{r} \right)^2 . \qquad (2)$$

With this expression we can estimate that $P \approx 1.5 \times 10^{-5}$ when $f_E \approx 0.1$ and $r = 3 \times 10^{12}$ cm for a homologous core mass of $M_5^{\rm HC} = 1$. This is an interesting figure of merit, since it is roughly the lowest reasonable value for the primordial deuterium abundance—any production above this value would correspond to D/H enhancement. A P value of 10^{-4} is not out of reach if f_E can be as high as 60%. We note that a baryon at $r = 3 \times 10^{12}$ cm for the indicated value of $M_5^{\rm HC}$ would have a gravitational binding energy of order 0.5% of its rest mass. The key question is whether there are any circumstances under which material with this binding energy could acquire enough thermal energy that ejection would be possible (Fuller & Shi 1997).

Here P will also be the amount of deuterium enrichment relative to hydrogen in the limit where the reaction $n(p, \gamma)$ D is fast compared to the material ejection rate and the free neutron decay rate and where the deuteron destruction process $\mathrm{D}(p,\gamma)^3\mathrm{He}$ is slow compared to the material ejection rate. In fact, such conditions can be attained for some outer regions of the supermassive star, as we illustrate in Figure 1. In this figure the material ejection timescale is taken to be the free-fall timescale, since they are typically of the same order. The stippled region corresponds to thermodynamic and expansion conditions where deuterium can be produced and can survive.

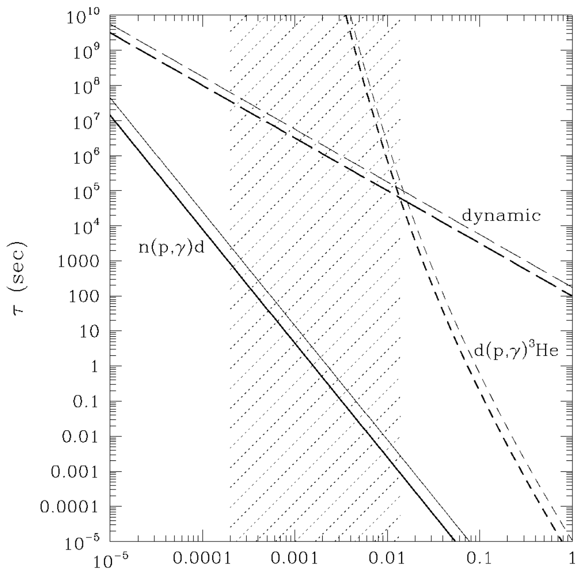

FIG. 1.—Timescale of $n(p,\gamma)$ D and $\mathrm{D}(p,\gamma)$ ^{3}He, and the dynamic timescale against the temperature (in units of 10^9 K) in the star, assuming the density in the star $\rho \propto T_9^3$. Heavier (lighter) lines are for $M_5 \approx 1(10)$. The stippled region corresponds to thermodynamic and expansion conditions where deuterium can be produced and can survive, for $M_5 \approx 1$. The region does not shift much for $M_5 \approx 10$.

The fate of the initial primordial deuterium in the envelope is unclear. Supermassive stars are convective during their precollapse contraction phase. If their convection proceeds faster than the contraction, and their central temperatures during most of the contraction phase are high enough to burn deuterium, the primordial deuterium may be destroyed in the entire star before collapse. This could occur in less massive supermassive stars whose central temperatures are higher.

3. ENVELOPES OF SUPERMASSIVE STARS AS Lyα ABSORBERS

Once the enriched envelope of a supermassive star is ejected, it expands freely in space and eventually cools down to $\sim 10^4$ K, in equilibrium with ambient UV radiation. Its expansion velocity is at least $\sim 10\ \mathrm{km\ s^{-1}}$, the thermal speed at 10^4 K. It can easily expand to a size of 1 kpc, unless it encounters another cosmic structure or is slowed down simply by loading of the ambient medium. The ambient baryonic mass swept up by the envelope is on average $(4\pi/3)R^3 \Omega_b \bar{\rho} \sim 10^3 \Omega_b h^2 (1+z)^3 (R/1\ \mathrm{kpc})^3\ M_\odot$, where $\bar{\rho}$ is the average matter density at a redshift z and R is the radius of the expanding envelope. At $z \sim 2$–3, this mass will be larger than the mass of the ejected envelope if $R \gg 1$ kpc. Therefore, the expansion of the envelope up to $R \sim 1$ kpc can be essentially free, and its chemical composition can be essentially unperturbed.

The number of such envelope systems in one quasar line of sight is

$$(\Omega_{\rm sms} \bar{\rho}/M) \pi R^2 l (t/t_0) \sim 300 \Omega_{\rm sms} h^2\ (1+z)^3\ (R/1\ \mathrm{kpc})^2 M_5^{-1}, \qquad (3)$$

where $\Omega_{\rm sms}$ is the density parameter of baryons in supermassive stars, M is mass, $l \sim 10^3$ Mpc is the proper distance interval under investigation in a quasar line of sight, $t \sim 10^8$ yr is the duration of the free expansion, and $t_0 \sim$ few $\times\ 10^9$ yr is the age of the universe at that time. Therefore, even if we assume that 10^{-5} of the mass of our universe (or 0.01% to 0.1% of baryons) is contained in these supermassive stars at $z \sim 2$–3, we can expect to see at least one such envelope absorber in tens of quasars. In comparison, there are reported detections from three Lyman-limit systems from surveys of ~ 100 quasars, a statistic that can easily be accommodated by these absorbers being ejected envelopes of supermassive stars.

The column densities of these ejected envelopes are approximately

$$x M_{\rm env}/\pi R^2 m_p \sim 10^{19} x (R/1\ \mathrm{kpc})^{-2}\ (M_{\rm env}/10^5\ M_\odot)\ \mathrm{cm}^{-2}, \qquad (4)$$

where x is the ionization fraction of the envelope, $M_{\rm env}$ is its mass, and m_p is the proton mass. With a temperature of $\sim 10^4$ K and the envelope in photoionization equilibrium with the ambient photoionizing UV background, $x \sim 10^{-2}$. Therefore the resultant column density is that of a Lyman-limit system, $\sim 10^{17}\ \mathrm{cm}^{-2}$, with $M_{\rm env}$ being a significant portion of the parent mass $\gtrsim 10^5\ M_\odot$.

Curiously enough, all three Lyman-limit systems with reported detections of D/H have double components. This is fully consistent with the geometry of ejected envelopes. The velocity separations between the double components range from 11 to 20 km s^{-1}, which can easily be produced if the envelopes expand at $\sim$ 10 km s^{-1}. The double components that yield the lower D/H are quite asymmetric, however. But one cannot rule out the expanding envelope scenario on this information alone because so far we have only considered the simplest case of spherical symmetry. Asymmetries can easily arise as a result of asymmetric ejections or structures in the ambient medium. The spectral profiles of the measured clouds indicate temperatures of $\sim 10^4$ K with small turbulence motion. Our freely expanding envelope scenario fits these features, too.

The explanation of low metalicities in these clouds with measured D/H is not a problem either because, even though the supermassive stars may undergo hot hydrogen burning and breakout to the *rp* process, they may not eject significant amounts of nucleosynthesis products from deep in their cores. These stars, however, could produce huge amounts of ^{4}He (FWW).

Selection criteria dictate that systems with high deuterium abundances are most likely to be picked out. Therefore, if Population III supermassive stars existed in the early stage of our universe and they ejected material, all or some of the three Lyman-limit systems with detected deuterium abundances may be accounted for by the ejected envelopes of these stars. The required population of these supermassive stars need not be great. One thousandth of baryons in the universe forming supermassive stars can be enough. There is no conflict in having a universe in which $\lesssim 0.1\%$ of its baryonic mass is in $\sim 10^5\ M_\odot$ black holes. Some of these black hole remnants of supermassive stars may even assume a role in galaxy formation by accreting mass and becoming the massive black holes observed at the center of many galaxies (van der Marel et al. 1997).

4. DISCUSSION

Thus far we have found the following results:

1. Antielectron neutrinos from the collapse of supermassive stars can produce enough free neutrons in outer layers of supermassive stars to boost the deuterium abundance there to $\sim 10^{-5}$–10^{-4}.

2. If the deuterium-enriched outer layers are ejected, they can reach a large enough size that they could mimic low-metallicity Lyman-limit absorbers at high redshifts. The chance of seeing such a Lyman-limit absorber in a quasar line of sight is about 1 in several tens if 0.01% to 0.1% of baryons are in supermassive stars at a redshift of 2–3, comparable to the current detection probability.

Here we especially stress that the ejecta cannot enhance the global deuterium abundance in any significant manner because (1) only a small fraction of baryons may be in the form of supermassive stars (otherwise most of the baryons now would be in black holes), and (2) only a small fraction of supermassive star material may be ejected as a result of the depth of the gravitational potential. However, we also note that since the chance of seeing such a local enrichment of deuterium in quasar lines of sight may not be low, we have to be extremely cautious before we can take a D/H measurement in Lyman-limit absorbers as primordial. So how can we assure ourselves that measurements of D/H in Lyα systems reflect the primordial value?

First, we do not expect most Lyman-limit systems to be envelopes of supermassive stars. On the other hand, the enrichment process is sensitive to the conditions in the parent stars and should not yield a uniform deuterium abundance. Consequently, if further observations yield significantly more detections with a concordant deuterium abundance, it is highly unlikely that we are measuring enriched values.

Second, if the size of Lyα absorbers with measured D/H is established by double quasar lines of sight to be $\gg$1 kpc, they cannot be ejecta of supermassive stars. Their deuterium abundances are therefore not enriched.

Third, the epoch of supermassive stars may not last long. Thus, observations by the *Hubble Space Telescope* of low-metallicity absorbers at $z < 1$ might avoid the enrichment problem. However, one should then also worry about the destruction problem, that is, whether these absorbers have been processed through stars and their deuterium has been destroyed (Jedamzik & Fuller 1997).

Ultimately, evidence for supermassive star processing through enhanced D/H values would suggest that there is some way in which neutrino-exposed ejecta can escape from fairly deep in the gravitational potential well of these stars, and the D/H values derived from Lyman-limit absorption systems could probe yet another aspect of structure formation in the early universe. Along with an enhanced helium abundance, an enhanced deuterium abundance in Lyα absorption systems may signal the existence of supermassive stars at high redshifts.

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