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THE IONIZING EFFICIENCY OF THE FIRST STARS

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ABSTRACT

We investigate whether a single population of first stars could have influenced both the metal enrichment and reionization of the high-redshift intergalactic medium (IGM) by calculating the generated ionizing radiation per unit metal yield as a function of the metallicity of stellar populations. We examine the relation between the ionizing radiation and carbon created by the first stars, since the evidence for the widespread enrichment of the IGM at redshifts $z \sim 3$–4 comes from the detection of C IV absorption. We find that the number of ionizing photons per baryon generated in association with the detected IGM metallicity may well exceed that required for a late hydrogen reionization at $z \sim 6$, by up to a factor of 10–20 for metal-free stars in a present-day initial mass function (IMF). This would be in agreement with similar indications from recent observations of the microwave background and the high-z IGM. In addition, the contribution from intermediate-mass stars to the total metal yield, neglected in past works, substantially impacts such calculations. Finally, a top-heavy IMF is not necessarily preferred as a more efficient high-z source of ionizing radiation, based on nucleosynthetic arguments in association with a given level of IGM enrichment.

Subject headings: cosmology: theory — early universe — intergalactic medium

1. INTRODUCTION

The first stars are expected to be cosmologically significant from at least two sets of observations of the high-redshift (z) intergalactic medium (IGM): (1) hydrogen reionization at $z \gtrsim 6$ (Becker et al. 2001) and (2) the persistent metallicity ($Z \sim 0.003\ Z_\odot$) seen in Lyα clouds up to $z \sim 5$ (Songaila & Cowie 1996; Songaila 2001). In principle, there should be a strong correlation between the integrated stellar output of metals and ionizing radiation (Giroux & Shapiro 1996 and references therein). Examining the connection between these two effects is critical for several problems in cosmology, including the degree to which a *single population of early stars* could have influenced both reionization and IGM metal pollution, and the accurate calculation of the IGM metallicity, $Z_{\rm IGM}$, from observations of metal line absorption, which depends on the assumptions made for the ionizing photon background (e.g., Giroux & Shull 1997). These issues are also pertinent to other fields that are constrained by the stellar history of the baryons, such as theories for baryonic dark matter candidates (Fields, Freese, & Graff 1998).

Current spectroscopic data imply that H I reionization may occur not far beyond $z \sim 6$ (Becker et al. 2001) and that He II reionization occurs at $z \sim 3$ (Kriss et al. 2001 and references therein). However, recent data suggest a higher level of ionizing radiation at $z \gtrsim 6$–9 than would occur in a scenario with "late" H I reionization at $z \sim 6$. These include observations of the following: the microwave background from the *WMAP* satellite, indicating a high Thomson optical depth of $\sim 0.17 \pm 0.04$ (Kogut et al. 2003) or early reionization at $z \sim 17 \pm 4$; the evolution of Lyman-limit systems and the IGM ionizing background (Miralda-Escudé 2003); and the observed redshift evolution of the Fe/Mg ratios in QSO emission-line regions (Hamann & Ferland 1999). Although these data are by no means conclusive, they indicate that the level of stellar activity at $z \gtrsim 9$ is potentially significant and that the reionization history of the IGM could be relatively complex, with periods of extended or double reionization for H I and/or He II (Venkatesan, Tumlinson, & Shull 2003; Cen 2003; Wyithe & Loeb 2003; Hui & Haiman 2003). Given the current best-fit cosmological parameters and the associated small-scale power available to the reionizing sources (Spergel et al. 2003), an unusually high conversion efficiency of baryons to ionizing radiation may be required (Somerville, Bullock, & Livio 2003; Ciardi, Ferrara, & White 2003).

At present, it is believed that almost all of the baryons at $z \gtrsim 3$ reside in the IGM, with an average enrichment of $Z_{\rm IGM} \sim 10^{-2.5}\ Z_\odot$ at $z \sim 3$ (Ellison et al. 2000). This is detected primarily through C IV absorption down to the lowest column density systems, corresponding to the "true IGM"; there is also some evidence for widespread O VI enrichment in this IGM component (Schaye et al. 2000). From this, one can roughly estimate the fraction of baryons that went into the first stars that made the IGM metals and the associated number of ionizing photons per baryon (Miralda-Escudé & Rees 1997; Haiman & Loeb 1997). However, there are two potential problems that we face in trying to constrain the effects of high-mass stars consistently through the degree of IGM carbon enrichment. First, the photons relevant for reionization come from the massive stars in the stellar initial mass function (IMF; stellar masses $\gtrsim 10\ M_\odot$), while carbon is produced dominantly by longer lived intermediate-mass stars (IMSs; ~ 2–6 $M_\odot$). These stellar products may not be mutually constraining if the IMF was different in the past. Second, for burst-driven star formation (not continuous), most of the carbon is produced ~ 0.5 Gyr after the starburst, an order of magnitude in time *after* the massive stars' Type II supernovae, which occur on timescales of a few tens of Myr and which could drive galactic winds. It then becomes unclear how the carbon is expelled from individual halos and distributed ubiquitously in the IGM by $z \sim 3$–5 (Songaila 2001).

In this Letter, we present calculations of the stellar ionizing efficiency as a function of stellar metallicity, Z_*, and of the generated metals. We specifically examine the relation between the integrated ionizing radiation and the output in carbon and

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oxygen as (1) these metals appear to be widely detected in the IGM but are primarily the products (and hence probes) of different parts of the IMF, and (2) carbon and oxygen are easily observed at typical IGM temperatures at $z \sim 2$–4. The point that carbon is primarily the product of IMSs while massive stars dominate the ionizing radiation is not new to this work and has been demonstrated extensively in the past (see, respectively, e.g., Iben & Truran 1978, and Tumlinson, Shull, & Venkatesan 2003 and references therein). Our main goals here are to investigate the implications of these stellar trends for cosmology, particularly for the reionization and metal enrichment of the high-z IGM. We focus on stellar nucleosynthetic arguments, from which we can derive the minimum number of ionizing photons that must have been generated in association with the observed levels of IGM enrichment at $z \sim 2$–5, including cases with the significant metal yield from IMSs.

2. RELATING STELLAR RADIATION AND METAL YIELDS

The first generations of stars are expected to be metal-free in composition (Population III) and rely more heavily on the *p-p* chain initially than on the more efficient CNO cycle for their thermonuclear fuel source. Consequently, they are hotter and emit significantly harder ionizing radiation relative to their finite-Z_* counterparts (Bromm, Kudritzki, & Loeb 2001; Tumlinson et al. 2003; Schaerer 2002, 2003). These objects could play an important role in either the single or extended reionization of H I and He II. The gain in ionizing radiation with metal-free stars depends on the assumed IMF. Recent theoretical studies indicate that the primordial stellar IMF may have been top heavy (Abel, Bryan, & Norman 2000; Bromm, Coppi, & Larson 2002), leading predominantly to stellar masses $\gtrsim 100\ M_\odot$.

As noted earlier, for a Salpeter IMF, all of the ionizing radiation and most of the metals, particularly the alpha-elements (e.g., oxygen), originate from the short-lived massive stars. With decreasing Z_* of the stellar population, the massive stars generate greater ionizing radiation and lower post-SN metal yield (Heger & Woosley 2002; Woosley & Weaver 1995). However, the opposite trend holds for the IMSs: a star of lower Z_* has greater metal yield (van den Hoek & Groenewegen 1997). Such constraints on stellar activity therefore alter with the average Z_* of star-forming regions and hence with redshift.

As a diagnostic of the relation between the generated ionizing photons and metals from stars, Madau & Shull (1996) introduced the conversion efficiency, $\eta_{\rm Lyc}$, of energy produced in the rest mass of metals, $M_Z c^2$, to the energy released in the H-ionizing continuum, defined as follows:

$$\eta_{\rm Lyc} \equiv E(h\nu \geq 13.6\ {\rm eV})/(M_Z c^2). \tag{1}$$

Madau & Shull (1996) found $\eta_{\rm Lyc}$ to have a relatively constant value[4] of 0.002 for solar values of Z_* and to be roughly independent of the stellar IMF's slope. This quantity can be used to calculate the number of ionizing photons per baryon in the universe generated in association with the observed IGM metallicity, $N_{\rm Lyc}/N_b$, defined as the ratio of the energy of the Lyman continuum (Lyc) photons per baryon to the average energy of a Lyc photon (Miralda-Escudé & Rees 1997). For solar-Z_* stars where $\eta_{\rm Lyc} = 0.002$, we have

$$N_{\rm Lyc}/N_b = (E_{\rm Lyc}/N_b)/\langle E_{\rm Lyc}\rangle = (\eta_{\rm Lyc}\langle Z_{\rm IGM}\rangle m_p c^2)/\langle E_{\rm Lyc}\rangle$$
$$\sim 0.002 \times 10^{-4} \times (1\ {\rm GeV}/20\ {\rm eV}) \sim 10. \tag{2}$$

This implies that, on average, 10 stellar ionizing photons per baryon were generated in association with the synthesis of the observed $Z_{\rm IGM} \sim 10^{-4}$, a reasonable value for a number of reasons. Given the observed decline in the space density of bright QSOs at $z \gtrsim 3$, high-redshift star formation is thought to have played a significant, if not dominant, role in reionization. Furthermore, although $N_{\rm Lyc}/N_b$ need only equal about unity for reionization, the effects of high-z recombinations in the IGM and individual halos likely boost the required $N_{\rm Lyc}/N_b$ to values close to about 10 (see Somerville et al. 2003).

However, $\eta_{\rm Lyc}$ is strongly dependent on Z_* and the IMF mass range, an effect that has not been studied until recently (Schaerer 2002). Thus, the above calculation of $\eta_{\rm Lyc}$ does not always lead to $N_{\rm Lyc}/N_b \sim 10$. Population III stars, having no metals, are hotter and emit harder radiation. When combined with the trend of lower metal yields with decreasing Z_*, we would expect a net decline in $\eta_{\rm Lyc}$ with rising Z_*. This has been recently demonstrated for a few specific cases by Schaerer (2002). However, the significant contribution by IMSs to the overall metal yield, particularly through carbon, has been neglected by past works (Schaerer 2002; Madau & Shull 1996), which assumed that massive stars were the dominant sources of the metals. Including the IMS contribution has a nonnegligible impact on the values of $\eta_{\rm Lyc}$ as well as on $N_{\rm Lyc}/N_b$, as we show below.

A concern in relating the ionizing photon and nucleosynthetic output of stellar populations is finding an overlap amongst the input Z_* and assumptions in the literature's calculations. At present, the ionizing photon spectrum for metal-free massive stars appears to be consistent amongst several works to within ~10% (Schaerer 2003; Tumlinson et al. 2003; Bromm et al. 2001). However, the stellar yields are not entirely convergent yet, with variations of up to factors of a few (see, e.g., Limongi & Chieffi 2002). We consider three values of Z_*: 0, 0.001, and 0.02 (i.e., solar), and two separate mass ranges, 1–100 $M_\odot$ and 100–1000 $M_\odot$. From here onward, we refer to the former mass range as a present-day IMF and to the latter as very massive stars (VMSs) or, equivalently, a top-heavy IMF. Although such clean distinctions may not exist for the first stars, we do this in order to differentiate the signatures of stars in these two IMFs. The metal yields are taken from van den Hoek & Groenewegen (1997) for stellar masses less than 8 $M_\odot$ and from Woosley & Weaver (1995) for the 8–40 $M_\odot$ mass range. Note that for $Z_* = 0.001$ massive stars, we use the $Z = 0.1\ Z_\odot$ case from Woosley & Weaver (1995). Since there are no detailed yields to date for $Z_* = 0$ IMSs, we use those for $Z_* = 0.001$ IMSs, which are not substantially different (A. Chieffi 2002, private communication). For $Z_* = 0$ VMSs, only the stars of mass 140–260 $M_\odot$ avoid complete collapse into a black hole (Heger & Woosley 2002) and contribute to the nucleosynthetic output. We note that the term yield in this Letter connotes the total ejected mass in individual elements or in metals and not the net yield after accounting for the original metal composition of the star.

We do not consider main-sequence mass loss in any of our cases below; this is unlikely to be important for low-Z_* stellar populations (see Tumlinson et al. 2003 on this point). We as-

[4] More recent unpublished calculations indicate that $\eta_{\rm Lyc} \sim 0.003$ for $Z_* = Z_\odot$ (J. M. Shull 2003, private communication).

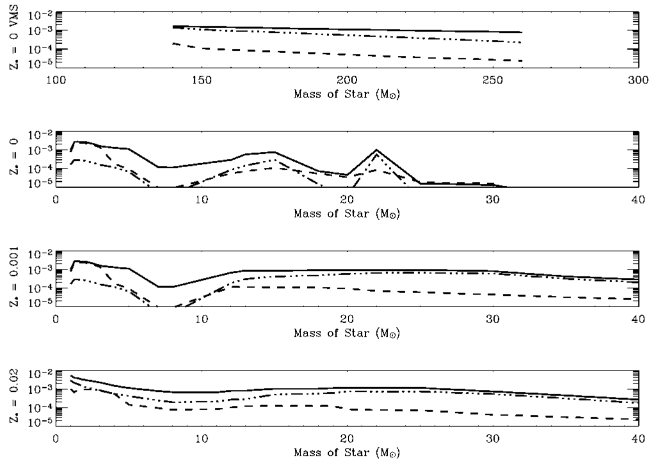

FIG. 1.—IMF-weighted total ejected masses of metals (*solid lines*), carbon (^{12}C; *dashed lines*), and oxygen (^{16}O; *dash-dotted lines*) as a function of stellar mass for a Salpeter IMF. *Upper panel*: $Z_* = 0$ VMSs in the mass range 100–1000 $M_\odot$. *Lower three panels*: stars of metallicity $Z_* = 0$, 0.001, and $Z_\odot = 0.02$ in the mass range 1–100 $M_\odot$.

sume the stellar IMF to have the form, $\phi(M) = \phi_0 M^{-\alpha}$, and the IMF slope, α, to be the Salpeter value of 2.35, since small slope variations have been shown to make little difference (Giroux & Shapiro 1996; Madau & Shull 1996; Schaerer 2002, 2003). All the cases here are normalized over their respective mass ranges as, $\int dM\, M\phi(M) = 1$.

For the ionizing spectra, we use Bromm et al. (2001) and Schaerer (2003) for a top-heavy IMF, Tumlinson et al. (2003) for 1–100 $M_\odot$, $Z_* = 0$ stars, and Leitherer et al. (1995) for nonzero Z_* cases. We note that the *time-integrated* ionizing photon number from VMSs happens to be roughly the same as that from $Z_* = 0$ stars in an IMF over 1–100 $M_\odot$, despite the greatly boosted ionizing *rate* from VMSs, owing to their brief lifetimes. The stellar emission rate of ionizing photons drops to less than 1% of its initial value after 30 Myr for a present-day IMF (Venkatesan et al. 2003), but takes only about 3.5 Myr for a top-heavy IMF (Schaerer 2003). The cause is directly related to the lifetimes of the longest-lived (metal-free) star that is relevant for reionization in each of the IMFs: a 10 $M_\odot$ star ($\sim 2 \times 10^7$ yr) versus a 100 $M_\odot$ star ($\sim 3 \times 10^6$ yr). The net difference in the time-integrated ionizing radiation is a factor of only ~1.4 (Bromm et al. 2001; Schaerer 2002, 2003).

Finally, for the conversion from $\eta_{\rm Lyc}$ to $N_{\rm Lyc}/N_b$, we assume that $Z_{\rm IGM} \sim 10^{-2.5}\, Z_\odot$, with the correspondingly scaled levels of carbon and oxygen with respect to their solar abundances[5] (Shull 1993 and references therein). We take $\langle E_{\rm Lyc} \rangle$ to be 21 eV for $Z_* = Z_\odot$ and $Z_* = 0.001$ stars, 27 eV for $Z_* = 0$ stars in a 1–100 $M_\odot$ IMF, and 30 eV for $Z_* = 0$ stars in a top-heavy IMF (Schaerer 2003).

[5] Note that the solar abundance values of some metals have been significantly revised in recent years. Although this is currently unresolved, we note that if we use, e.g., Holweger (2001), the values of $N_{\rm Lyc}/N_b$ in this work will increase slightly for carbon and decrease by about 30% for oxygen.

3. RESULTS

We first show that carbon and oxygen are mostly the products of IMSs and massive stars, respectively, and that IMSs are consequently significant contributors to cosmological metal generation. Figure 1 displays the total IMF-weighted yields for metals, ^{12}C, and ^{16}O as a function of stellar mass for VMSs and for three values of Z_* for a present-day IMF. Using the total ejected mass, M_i, in each element or metals as a function of stellar mass M, the y-axis in the figure is calculated by weighting each M_i with the IMF as $M_i\phi(M)$. Using the yields and ionizing spectra as described in § 2, we calculate $\eta_{\rm Lyc}$ and $N_{\rm Lyc}/N_b$ in Table 1 for several cases: (1) as a function of Z_*, (2) as defined with respect to total metal, ^{12}C, and ^{16}O yield, and (3) with metal yields included from three mass ranges (1–100 $M_\odot$, 8–100 $M_\odot$, and 100–1000 $M_\odot$). In the second case, the conversion from $\eta_{\rm Lyc}$ to $N_{\rm Lyc}/N_b$ involves two factors that will cause $N_{\rm Lyc}/N_b$ to vary within each column in the table: $\eta_{\rm Lyc}$ and $Z_{\rm IGM}$, which will both vary at fixed Z_* depending on whether we are considering $\eta_{\rm Lyc}$ and $N_{\rm Lyc}/N_b$ with respect to total metals, ^{12}C, or ^{16}O. The last case is intended to evaluate the impact of the metal contribution from various regions of the stellar IMF, particularly from IMSs, on $\eta_{\rm Lyc}$ and $N_{\rm Lyc}/N_b$.

The results in Table 1, although subject to the uncertainties in stellar modelling, reveal several trends of interest to high-z IGM studies. These may be summarized as follows.

First, $\eta_{\rm Lyc}$ can vary significantly with Z_* and with the element with respect to which it is defined. As anticipated for the reasons outlined in § 2, there is a strong gain in $\eta_{\rm Lyc}$ and $N_{\rm Lyc}/N_b$ as Z_* decreases, with $Z = 0$ stars in a present-day IMF being up to 10–20 times more efficient at generating ionizing radiation per unit metal yield than the $Z = Z_\odot$ stars in Madau & Shull (1996).

Second, although the values of $\eta_{\rm Lyc}$ approximately match those of, e.g., Schaerer (2002), when the yields from IMSs are excluded, we see that IMSs are in fact a substantial source of metals, particularly carbon, and should be included in such calculations. One possible exception might be at very high redshifts, when IMSs may not have had the time yet to eject their nucleosynthetic products. In this case, the original definition (Madau & Shull 1996) of $\eta_{\rm Lyc}$ which does not include IMS metal yields would be valid, and $\eta_{\rm Lyc}$ may be stated to increase with decreasing Z_* and/or increasing redshift.

Third, $\eta_{\rm Lyc,O}$ is the most sensitive to Z_*, increasing strongly from solar-Z_* to metal-free stars, for a present-day IMF. This directly results from the following three trends: (1) ^{16}O and ionizing radiation are produced dominantly by the IMF's mas-

TABLE 1
IONIZING EFFICIENCY AS A FUNCTION OF STELLAR METALLICITY

	$Z_* = 0$	$Z_* = 0$ (1–100 $M_\odot$)		$Z_* = 0.001$ (1–100 $M_\odot$)		$Z_* = Z_\odot$ (1–100 $M_\odot$)	
η	(10^2–10^3 $M_\odot$)	$M_Z(\geq 1\ M_\odot)$	$M_Z(\geq 8\ M_\odot)$	$M_Z(\geq 1\ M_\odot)$	$M_Z(\geq 8\ M_\odot)$	$M_Z(\geq 1\ M_\odot)$	$M_Z(\geq 8\ M_\odot)$
$\eta_{\rm Lyc,Z}$ ($N_{\rm Lyc}/N_b$)	0.005 (11)	0.035 (81)	0.08 (186)	0.006 (18)	0.008 (24)	0.003 (9)	0.004 (13)
$\eta_{\rm Lyc,C}$ ($N_{\rm Lyc}/N_b$)	0.098 (32)	0.086 (31)	0.48 (173)	0.025 (12)	0.088 (41)	0.02 (9)	0.048 (22)
$\eta_{\rm Lyc,O}$ ($N_{\rm Lyc}/N_b$)	0.01 (10)	0.15 (172)	0.2 (223)	0.013 (18)	0.013 (19)	0.005 (8)	0.007 (10)

NOTES.—The conversion efficiency of rest mass in metals, carbon, and oxygen to ionizing radiation and the associated number of ionizing photons per baryon, as a function of stellar metallicity, Z_*, and the mass range of the stellar population. Cases are also shown with metal contributions from different regions of the stellar IMF. All models assume a Salpeter slope for the IMF.

sive stars, (2) with decreasing Z_*, the production of ^{16}O decreases while that of ionizing photons increases, and therefore, (3) their ratio $\eta_{\rm Lyc,O}$, in comparison with $\eta_{\rm Lyc,Z}$ or $\eta_{\rm Lyc,C}$, shows the strongest increase with declining Z_* for stars in a present-day IMF.

Fourth, the value of $\eta_{\rm Lyc}$ directly impacts the fraction of baryons required to be converted into a first stars' population in order to influence reionization (e.g., Bromm et al. 2001; Miralda-Escudé & Rees 1997). One possible implication of the first result above is that a factor of 10–20 fewer baryons need to be part of such a population for them to be relevant for reionization alone (which requires only $N_{\rm Lyc}/N_b \sim 10$), if such stars are not required to account for $Z_{\rm IGM}$. In this case, reionization by Population III stars in a present-day IMF occurs late (since they should generate fewer ionizing photons than indicated by Table 1), and such stars would therefore make a negligible contribution to the carbon detected in the high-z IGM, particularly at $z \gtrsim 6$. An alternate interpretation of Table 1, assuming that the IGM is relatively uniformly enriched by volume, is that $Z = 0$ stars (1–100 $M_\odot$) created the IGM metals and consequently, reionization may occur early. This is because the values of $N_{\rm Lyc}/N_b$ (~30–220) generated by these stars in association with the detected $Z_{\rm IGM}$ well exceeds that required for a late H I reionization at $z \sim 6$. If clusters of such stars are responsible for both the reionization and metal enrichment of the IGM, they should be easily detected by future missions such as the James Webb Space Telescope (Tumlinson et al. 2003; Tumlinson, Giroux, & Shull 2001), and the amount of star formation at $z \gtrsim 9$ is potentially significant (§ 1).

Finally, despite their high ionizing photon *rate*, VMSs are *less* efficient at generating total ionizing radiation *per unit metal mass* than are metal-free stars in a present-day IMF, owing to the greatly boosted metal yield from a top-heavy IMF. (Both of these stellar populations, however, have approximately equal $\eta_{\rm Lyc,C}$, with the difference being largest when IMSs are excluded or, equivalently, at $z \gtrsim 6$.) Therefore, VMSs are not necessarily preferred as a more efficient source of ionizing radiation at early epochs on nucleosynthetic grounds in association with a given detected level of IGM enrichment, and possibly based on reionization requirements as well (see, e.g., Somerville & Livio 2003). Furthermore, recent studies (e.g., Schneider et al. 2002) indicate that the transition from a top-heavy to a present-day IMF occurs at gas metallicities of about $10^{-4}\ Z_\odot$. If this were true, then we can scale down the numbers for VMSs in Table 1 down by 1.5 orders of magnitude and derive that VMSs may produce only ~0.35 ionizing photons per baryon for an IGM metallicity of $10^{-4}\ Z_\odot$ before they pollute their environments and cease forming. We emphasize, however, that VMSs may still be important for reionization alone, given the right combination of conditions, owing to their high ionizing rates.

The conversion between $\eta_{\rm Lyc}$ and $N_{\rm Lyc}/N_b$ does not account for the relative propagation timescales of metals and photons from star-forming regions to the IGM, which will impact the evolution of IGM abundance ratios between individual elements, e.g., [C/O]. Furthermore, the definition of $\eta_{\rm Lyc}$ implicitly assumes the instantaneous creation of the metals. This is not necessarily true at high redshifts, e.g., to generate sufficient carbon at $z \sim 3$–6 requires the star formation to have occurred at $z \gtrsim 6$–9. As we noted earlier, this becomes particularly problematic for the transport of the carbon to the IGM through SN-driven winds. We explore the cosmological relevance of these timescale issues in more detail in a forthcoming paper.

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