Impacts of the 16O(16O, n)31S reaction rate on the evolution and nucleosynthesis in Pop III massive stars

Authors: Xin, Dr. Wenyu, Nomoto, Prof. Ken ‘ichi, Zhang, Prof. Xianfei, Bi, Prof. Shaolan, Xin, Dr. Wenyu

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Abstract

We present a systematic investigation into the effect of the 16O(16O, n)31S reaction rate on the evolution and nucleosynthesis of Population III (Pop III) stars. We simulate the evolution of Pop III stars with initial masses of 15, 20, 30, and 40 M from the zero-age main sequence through to core collapse. The 16O(16O, n) sup>31S reaction rate is investigated by factors of 0.1, 1.0, 5.0, and 10.0. Our results demonstrate that increasing this reaction rate prompts earlier onset and extended duration of core oxygen burning at lower temperatures and densities. A higher reaction rate also increases neutron excess in OSi-rich layers, thereby promoting the synthesis of neutron-rich isotopes. In particular, the yields of the odd-Z elements, P, Cl, K, and Sc, are enhanced while those beyond O burning, for example, Ti, are not sensitive to this reaction rate. By comparing with the observed abundances from extremely metal-poor stars, we find that increasing this reaction rate from the CF88 compilations by a factor of 5.0 leads to predicted abundance ratios [K/Ca] and [Sc/Ca] that fall within the observational ranges.

Full Text

Preamble

Impacts of the O, n) S reaction rate on the evolution and nucleosynthesis in Pop III massive stars Wenyu Xin, 1, 2, Bingyang Tan, Ken’ ichi Nomoto, Xianfei Zhang, and Shaolan Bi 1 Institute for Frontiers in Astronomy and Astrophysics, Beijing Normal University, Beijing 102206, People’ s Republic of China School of Physics and Astronomy, Beijing Normal University, Beijing 100875, People’ s Republic of China CAS Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, People’ s

Republic of China School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, People' s Republic of China Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan We first present a systematic investigation into the effect of the O, n) S reaction rate on the evolution and nucleosynthesis of Population III (Pop III) stars. We simulate the evolution of Pop III stars with initial masses of 15, 20, 30, and 40 M from the zero-age main sequence through to core collapse. The S reaction rate is investigated by factors of 0.1, 1.0, 5.0, and 10.0. Our results demonstrate that increasing this reaction rate prompts earlier onset and extended duration of core oxygen burning at lower temperatures and densities. A higher reaction rate also increases neutron excess in OSi-rich layers, thereby promoting the synthesis of neutron-rich isotopes.

In particular, the yields of the odd-Z elements, P, Cl, K, and Sc, are enhanced while those beyond O burning, for example, Ti, are not sensitive to this reaction rate. By comparing with the observed abundances from extremely metal-poor stars, we find that increasing this reaction rate from the CF88 compilations by a factor of 5.0 leads to predicted abundance ratios [K/Ca] and [Sc/Ca] that fall within the observational ranges.

Keywords

massive stars, supernovae, nuclear reactions, nucleosynthesis

INTRODUCTION

After the Big Bang, the primordial gas was composed pri- marily of hydrogen and helium, with minor contributions from light elements such as lithium, beryllium, and boron.

The heavier elements were subsequently synthesized during the evolution and explosion of the first stars, referred to as Population III (Pop III) or metal-free stars. These massive stars concluded their lives as the first supernovae, thereby in- jecting large quantities of energy and newly synthesized met- als into the interstellar medium. This profoundly affected the early galaxies, influencing their dynamics, thermal properties, and chemical composition. However, observing these first

stars presents a significant challenge, as they are likely to exist 13

in the most distant reaches of the universe. Long-lived, low- 14

mass, metal-poor stars serve as crucial observational probes

for constraining the characteristics of the first stars, as they 16

preserve the nucleosynthetic imprints of the first supernovae

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in their surface abundances [

In the early universe, the primordial gas was characterized 19

by an extremely low metal content, and the neutron excess in Pop III stars remained nearly zero until the completion of he-

lium burning. However, the 12 C(12 C, n) 23 Mg reaction plays a 22

crucial role, as the frequent decay of Mg to Na enhances

the neutron excess during the carbon-burning phase [4 , 5]. 24

Subsequently, the O, n) S reaction, along with var-

ious weak interaction processes during the oxygen-burning 26

phase, can further increase the neutron excess ( ). Given that oxygen is more abundant than carbon in the carbon-oxygen (CO) core, a substantial number of protons are converted into neutrons throughout both the central and off-central re- gions. The neutron excess is not only important for nucle-

osynthesis during the advanced stellar burning stages [4], but 32

also affects the electron mole fraction ( ), within the star,

where $\eta = 1 - 2$ Y e . The value of Y e decreases significantly 34

near the bottom of O burning, which subsequently impacts 35

the iron (Fe) core mass and final explosion [ ]. Ad- ditionally, the O, n) S reaction may serve as a tron source for the s-process in massive stars.

The total reac- tion rate for C and its branching rate have been mea- sured and constrained by Bucher et al.] and Low-Energy and high-Charge-state Heavy Ion Accelerator Facility (LEAF]), and the related impact on the stellar evolution and nucleosynthesis has also been investigated by Chieffi et al.], Xin et al.], Dumont et al.]. However, for the to- O and the branching reaction rates, particularly for

16 O(

O, n) S, there have not yet been many experimental measurements and sensitivity investigations.

Previous studies from Dumont et al.] and Farmer et al.

] investigated the effects of the total O reaction rate

on the progenitors of the core-collapse supernovae (CCSNe)

and the evolution of pulsational pair-instability supernovae (PPISNe), respectively. However, these studies did not ex- amine the effects of individual branching reactions. Fields et al.] reported that varying the O, n) S reaction rate by a factor of 10 may slightly change the central approximately 4%. However, their investigation was limited

to solar and subsolar metallicity stars. In Pop III stars, the ini-

tial neutron excess is exactly zero. Even a modest change in the neutron excess can exert a pronounced influence on stellar structural evolution and nucleosynthetic yields.

To illustrate the importance of the O, n) S reaction rate and motivate the subsequent experimental measurement, we systematically examine the effects of the O, n) reaction rate on the evolution and nucleosynthesis of Pop III

stars for the first time. The paper is organized as follows:

Section describes the adopted stellar models and details the input assumptions, establishing the basis for our study. Sec- presents the simulation results in detail. Section provides a discussion of the implications of our findings and summarizes the main conclusions of this work.

METHODS AND MODELS All calculations in this work were performed using the Modules for Experiments in Stellar Astrophysics (MESA, version 24.08.1; Paxton et al.], Jermyn et al.

to track nuclear burning processes and structural evolution

in stars with the zero-age main sequence (ZAMS) mass of

M (ZAMS) = 15, 20, 30 and 40 M from the ZAMS until the

Fe core collapse, defined as the point where infall speed of the Fe core reaches 1000 km s Presupernova Evolution

The initial chemical composition of Pop III stars is as-

sumed to reflect primordial Big Bang nucleosynthesis, as re- ported by Steigman [ ]. The mass fractions for

4 He, and

Li are 0.7516, 4.01 , 2.39 , 0.2483,

and $2.26 \times 10 - 9$. No heavier nuclides than A $>$ 7 are produced in astrophysically interesting abundances during Big Bang nucleosynthesis.

Given that Pop III stars are metal-free, stellar wind mass loss is considered negligible in our calculations.

Convective boundaries in our models are determined using the Ledoux criterion, and semiconvective mixing is implemented with an efficiency parameter α sc =

0.01. Following

the simulation of Brott et al.], step overshooting is applied

during core hydrogen burning with α ov = 0 . 335 . After core hydrogen burning, exponential overshooting is implemented at the top of core helium burning with f ov = 0 . 01 , and a small degree of overshooting (f ov = 0 . 005) is used at the tops of all other convective cores to suppress numerical artifacts. No overshooting is applied at the base of the shell helium burning. Because the structure is expected to evolve faster than

convection can reach a steady state in the late burning stages,

we employ the time-dependent convection (TDC), which is now included in the MESA code and described in detail by Jermyn et al.

Element Element To calculate nucleosynthesis, we adopt a nuclear network hydrostatic stellar evolution. The isotopes included in this network are outlined in Table . Following our previous studies [ ], The nuclear reaction rates are taken from the latest To simulate the shock propagation and explosive nucleosynthesis explosion, employ example_{{{ccsn}}_{{IIp}}} setup in MESA. We simulate the supernova shock by placing a "thermal bomb" at the center of the models following the approach described in [

First, we adopt an initial mass cut at the outer boundary of

the Fe core (Y e 0.48; [31 , 32]), so that the oxygen-burning

shells are entirely included in the ejecta and the abundances

of oxygen-burning products reach a maximum. This configuration enables us to investigate the impact of O, n) reaction rate. We also compare the results with those adopt-

ing M cut = M 4 , which is defined at S = 4 k B /baryon and

widely used in previous studies [ ]. The difference in adopting these two mass cuts is approximately an issue of

whether the Si shell is included in the initial remnant. The

material interior to the mass cut is assumed to collapse into the compact remnant. We assume that no fallback and mixing occur during the explosion, and the ejecta mass corresponds to the mass exterior to the mass cut.

To initiate the explosion, we inject a finite amount of

energy into a thin shell of 0.01 M near the initial mass

cut, so that the total energy of stars reaches inject_{{{until}}*{{reach}}*}{{{model}}*{{with}}*}{{{total}}_{{en

gy = 1d51). This approach ensures that the resulting

explosion possesses a prescribed net energy, accounting for

the gravitational binding energy of the progenitor’ s envelope.

The energy is deposited over a characteristic timescale of

t inj = 5 ms, launching a hydrodynamic shock wave that

propagates outward. As the shock propagates, it heats the

material and ignites nuclear burning. The star is then evolved

until the maximum temperature in the ejecta drops below K, by which time the shock has cooled sufficiently that no further nucleosynthesis occurs, except for decays.

Finally, post-processing is performed until all isotopes decay to stable species.

C. Reaction Rates in O Burning

The O burning ignites when the temperature reaches 1.9

] and proceeds explosively over the temperature range of 3 - 4 GK. In the O fusion reaction, the compound states of 32 S are formed and decay via four channels,

28 Si +

Caughlan and Fowler [ ] (CF88) provides the standard and most widely adopted O reaction rate used in stel- lar evolution calculations. Owing to the experimental chal- lenges posed by oxygen targets and the existence of complex decay channels, all the measurements are limited to the ener-

gies above E c . m . =

6.7 MeV, slightly higher than the median

of the Gamow window [ ]. Thus, the extrapolation is necessary to obtain the S-factors covering an entire Gamow window. Compared with the S-factors reported by CF88, the measurements of Wu and Barnes [ ] and the theoretical advancement of Dumont et al.], Islam et al.] both sug- gest an overall decreasing trend in the astrophysical S-factor

within the hydrostatic burning regime. In contrast, the mea-

surement reported by Hulke et al.] indicates an increasing

trend by a factor of 2 at E c . m . = 6.7 MeV.

channels as adopted in JINA REACLIB, noting that the deuteron channel is not included. The branching ratios during

hydrostatic burning for the neutron, proton, and α channels

are 15%, 65%, and 20%, respectively. At higher tempera- tures, the deuteron channel becomes accessible, with branch- ing ratios for neutron, proton, deuteron, and of 5%, 56%, 5%, and 34%, respectively [Given that many recent measurements only provide the S- factor of the O reaction, and latest reaction-rate table, covering the entire temperature range from 0.1 - 10 GK, are not released by Islam et al.] and Dumont et al.], we still adopt the reaction-rate table from CF88. To investigate

its effect, we scale this reaction rate by factors of f 16O = 0 . 1 ,

1.0, 5.0, and 10.0, while holding all other branching rates un- changed. Accordingly, the total O reaction rate during

hydrostatic burning is altered by approximately 0.85, 1.00,

1.67, and 2.51 times, respectively. It should be noted that ap- plying a single global scaling factor across all temperatures is a simplified approximation, although this method is also adopted in Fields et al.] and Farmer et al.]. Based on the evaluation of the recent measurements and theoretical ad-

vancement, we consider f 16O = 5.0 as a possible upper limit

for the this reaction rate and f 16O = 10.0 is an extreme test.

EVOLUTION AND NUCLEOSYNTHESIS OF PRE-SUPERNOVAE

A. Effect on the Core O Burning

evolution of core masses from the end of core helium burning

to the onset of Fe core collapse for M (ZAMS) = 15 M and

the default reaction rate (f 16O = 1). Here, t final is defined as the moment when the infall speed of the Fe core reaches 1000

The compactness parameter is defined at M r = 2.5 M and

used to evaluate the explodability [

ξ M r = M r / M R (M r) / 1000 km (2)

where is the enclosed mass at the radius of

After core helium burning, ξ 2 . 5 increases as the core contracts. The residual carbon mass fraction in the core,

= 0.285, is sufficient to ignite central carbon burning.

West

et al.] and Nomoto and Xin [ ] have shown that is sensitive to both the 3 O reaction rates.

Nevertheless, C) remains at most 0.5, even when the

12 C(

O reaction rate is varied within its uncertain-

ties. During the central carbon burning phase, the growth of

slows down, as the energy generated by the convective

(ZAMS) . The inner part of is shown. The blue and grey regions represent the convection and overshooting. The blue, orange, green, and black dashed lines show the variation of the CO core mass, O core mass, Si core mass, and Fe core mass. The boundaries of these cores are defined where Si) decrease down to 10

core retards further contraction. After core carbon burning,

the core contracts rapidly, triggering vigorous off-center carbon burning. As contraction proceeds, carbon burning is repeatedly ignited in the shell layers, becoming progressively

more energetic. The convective shell extends outward, transporting fresh C to its base to sustain burning. Conversely, the

increasingly intense shell carbon burning releases sufficient

energy to inhibit further contraction or even drive expansion.

Subsequent core and shell oxygen, silicon burning produce the ’ knees’ in the evolution track of . This evolutionary behavior is discussed in detail by Xin et al.] and Chieffi and Limongi [Although the branching ratio of the O, n) S chan- nel is small, increasing this reaction rate nonetheless produces

two significant effects. First, it elevates the total 16 O+ 16 O

fusion rate and, consequently, the nuclear energy generation rate associated with the O reaction, as described by Woosley et al. where O) denotes the mass fraction of O during oxy-

gen burning and λ 16 , 16 is the total 16 O+ 16 O fusion reaction

rate. With a higher nuclear energy generation rate, the core O

burning is ignited at lower central temperatures and densities.

In Figure 3 [Figure 3: see original paper] , the models with M (ZAMS) =

15 M

are pre-

sented as representative examples. We define the ignition of

core O burning as the point at which the energy generation

rate of the O reaction equals the neutrino energy loss

rate. We observe that with f 16O = 0 . 1 , the models undergo

core O burning at similar temperatures (1 . 62 × 10 9 K),

whereas the central temperatures decrease slightly, as , and the mass fractions of O and P at the center for (ZAMS) =

15 M

The time is defined at O ignition for each model, where the energy generation rate of O reaction equals the energy loss rate of neutrinos. increases.

Additionally, owing to the enhancement in the to- O reaction rate, the central oxygen mass fraction at

the O ignition decreases from 0.731 to 0.702. According to

Equation is enhanced by factors of 0.85, 1.00, 1.45,

and 2.22 for f 16O = 0.1, 1.0, 5.0, and 10.0, respectively. Rel-

ative to the default rate (f 16O = 1 . 0), reducing the 16 O(16 O,

S reaction rate by a factor of 10 decreases by only about 15% and the evolution of the central temperature and of O) remains largely unchanged. contrast, increasing the rate by a factor of 5.0 and 10.0 results in a more pronounced increases in , driving oxygen burning to occur at lower temperatures and densities. 256

Consequently, oxygen is consumed more slowly, extending

the core oxygen-burning lifetime to approximately 1.42 and 258

2.10 years, respectively. Once the central oxygen is depleted, the central temperature rapidly rises owing to continued core contraction. Table presents the results for the other models

during core oxygen burning. 262

B. Effect on Shell O Burning and Nucleosynthesis 263

Increasing the O, n) S reaction rate produces more 31 S, which subsequently decays to P. This decay process

alters the electron fraction Y e in the shell O burning. 266

temperature for different f 16O values for M (ZAMS) = 15 268

. In the Fe core and the base of the silicon shell (

1.35 M

), variations in the O, n) S reaction rate do not affect , as the temperature in this region is sufficiently

high to achieve complete silicon burning and nuclear statis- 272

tical equilibrium (NSE), which are independent of individ-

ual reaction rates. However, this rate significantly impacts 274

from the top of the silicon-rich layers up to the ONe shell (

1.8 M

In these regions, creases markedly as increases. discontinuity

, and represent the central temperature, density at O ignition, and the lifetime of core O burning. represents the maximum mass fraction of the center. (ZAMS) (g cm

Y e and temperature in the center for different f 16O at t = t final . The light blue, light green, and orange regions represent the Si, ONe, and CO layers.

typically occurs near the base of the oxygen-burning shell. 278

For f 16O = 1 . 0 , we observe a Y e jump within the silicon- 279

rich layers, attributable to the merger of the silicon-burning 280

shell with the oxygen-burning shell (see Figure 2 [Figure 2: see original paper]). The CO 281 shell (

1.8 M

) is largely insensitive to this reaction

rate because temperatures are not sufficiently high to ignite

oxygen burning. Although a decrease in Y e is observed for

f 16O = 10 , we also note an outward extension of convec-

tive shell oxygen burning in this model prior to core collapse,

which subsequently mixes lower- material outward. The altered distribution in the ONe and portions of the silicon- rich layers will also influence the resulting nucleosynthesis.

Approximately 90% of the products of oxygen burning are

28 Si and

32 S. The remaining products include 33 , 34 S, 35 , 37 Cl,

K, and Ca. Figure presents the isotope

16O = 0.1, 1.0, 5.0, and 10.0 at t = t final for M (ZAMS) =

15 M

.

yields from Si to Ca for f 16O = 0.1, 1.0, 5.0, and 10.0 at

t = t final . Elements heavier than Ca are predominantly syn-

thesized during silicon burning and the NSE process, which

are not significantly affected by the 16 O(16 O, n) 31 S reaction

rate. Slight variations in the yields of Ar, and 40 Ca may arise from temperature differences during oxy-

gen burning and the extent of convective regions. We find

that most neutron-rich isotopes—such as K, and Ca—are sensitive to changes in O, n) S reaction rate. The yields of these iso- topes are enhanced by approximately 3 to 10 times as the

reaction rate is varied by two orders of magnitude. Partic-

ularly, the yields of Cl, and K rise by factors of 2.8, 2.8, and 3.8, respectively. In contrast, other neutron-rich iso- topes are relatively insensitive to this reaction rate, since and 46 Ca are produced during carbon and neon burning, and 309

44 Ca originates almost entirely from the decay of radioactive

44 Ti formed in the

-rich freezeout. Note that the yields of some aforementioned isotopes are below and are not displayed in Figure THE CORE COLLAPSE SUPERNOVAE The nucleosynthetic yields from CCSNe are the result of (i) the structure and composition of pre-supernovae; (ii) whether or not the star can successfully explode and produce ejecta.

Final Structure and Explodability In this section, we discuss which models can explode suc- cessfully and produce ejecta. In Table , we present the core masses and explodability parameters for our models. though the compactness parameter is easier to estimate, it is not a good tool for predicting the explosion outcome [We predict the explosion outcome of our models based on the density profile [ ]. If a steep gradient of density or a density jump is present near the bottom of the O shell burn-

ing, the stars are likely to explode easily. The strength of the density jump is measured by two non-dimensional quantities log ( ) and log in Xin et al. defined in earlier studies [

U dln M r dln r = 4 πr 3 ρ M r (4) 331

V − dln P dln r = GM r ρ rP (5) 332

Here, , respectively, show the steepness of the gradients of log and log against log . log (and log represent the maximum of log and the

minimum of log U near the Si/O interface. As discussed 336

in Xin et al.], log ( ) and log represent the

strength of the shell O burning and the density jump. We use 338

to indicate the mass coordinate corresponding to log (in this work. The density profiles are steeper for the models

with M (ZAMS) = 15 (red circles) and 30 (green diamonds) 343

M , while those with M (ZAMS) = 20 and 40 appear com- 344

paratively flatter. This indicates that the 15 and 30 M els are easier to explode, while the others are not. The den-

sity jump arises from shell burning. Near the O/Si interface, 347

shell O burning remains active until core collapse. This re- 348

leases extra energy and heats the outer layers, counteracting their contraction. Concurrently, the inner Si core contracts, thereby increasing the core density. The density jump thus corresponds to the place of strongest shell oxygen burning,

which can be indicated by different (ZAMS) = 15 (red), 20 (orange), 30 (green), and 40 (blue) M = 0.1, 1.0, 5.0, and 10. The location of the density jump is indicated by The density jump in these models appears at

1.8 M

, except for the 20 M models. Near M (ZAMS) =

20 M

, the core C burning transitions from convective to radioactive due to the small residue of carbon after core He

burning. Lacking a convective central C burning accelerates

the contraction in the core, leading to a more compact core

and likely to collapse into a BH. As shell burning strengthens

in higher mass stars, the density jump returns to the region of 1.5 - 1.8 M , which leads to the formation of a non-

monotonic “compact island” near the transition mass. More

details for this change have been investigated by Xin et al.], Chieffi et al.], Sukhbold and Adams [ ]. We quan- tify the strength of the density jump with the strength of shell

O burning, log (V/U max), and predict whether these models

explode or not by log (V/U max) = 1.205 +0 . 070 − 0 . 055 , a criterion 3

suggested in Xin et al.], Nomoto and Xin [ ) as a function of (ZAMS) final = 0.1, 1.0, 5.0, and 10.0, respectively. Symbols above the gray band represent that the models undergo a successful explosion and forms a NS, while those below the gray band denote models that would not be expected to produce successful explosions (and thus ejecta). The dashed line and gray band represent log (reported by Xin et al.]. The dashed line represents the critical value to distinguish the successful explosion and collapse, and its uncertainty donates a nearby region where the final fates of the models are sensitive to the choice of criteria because too close to the critical line.

In Figure 7 [Figure 7: see original paper] , stars with log (V/U max) > 1.275 can explode

as supernovae and eject their outer layers, whereas those with

log (V/U max) < 1.15 are likely to collapse into BHs. The explodability of stars lying within the gray band should be sen- sitive to the choice of criteria because they are too close to the critical line. Consequently, stars with M (ZAMS) = 15 and

30 M

can explode successfully but those with M (ZAMS) =

20 M

are not. Stars with M (ZAMS) =

40 M

collapse into BHs for f 16O = 0.1, whereas they fall into the uncertain region because the strength of the shell O burning is enhanced for higher . Given the inherent uncertainty in the explodability of progenitors, we consider three distinct explosion scenarios in the subsequent discussions: (1) Uniform Explosion, where all progenitors undergo successful explosions; (2) Mass Truncation, where stars with M (ZAMS) >

3 See also Boccioli

et al.] for another criterion to predict explodability.

30 M

are assumed to collapse into black holes without material ejection. Since the stars M (ZAMS) =

40 M

are more likely to collapse into BHs in other studies [ ]; (3) Density-jump-Selected, where only stars with M (ZAMS) = 15 and 30 M undergo successful explosions while stars with M (ZAMS) = 20 and 40 M are not, based on the prediction of log (V/U) max = 1.205 in Figure 7 . 391

COMPARE WITH OBSERVATION To facilitate a direct comparison between our nucleosyn- thesis results and the observed abundance patterns of ex- tremely metal-poor stars, we calculate the relative abundance ratios. The abundance ratio of element i relative to element j is defined as: log((where represent the number of elements i and j, respectively. The solar abundance adopted here is from Lod- et al.

In Section , we first compare the abundance ratios of [K/Ca] predicted in this study with those of previous stud- ies, and discuss some uncertainties that aren' t included in this study. In Section , we will integrate these yields based on different explosion assumptions and discuss the contribution of these Pop III stars to the galactic chemical enhancement.

Potassium Elemental Abundance

Among the O burning products, the odd-Z elements, phos- 409

phorus (P), chlorine (Cl), and potassium (K), which are im- portant for planet formation and life, remain poorly under- stood. Supernova models systematically underproduce these

elements by up to an order of magnitude across all metallici- 413

ties [ ]. Recent XRISM observation indicates an enrich- ment of Cl and K in the solar neighborhood [ ] and Ishigaki et al.] reported enhanced K in the surface of EMP stars.

As Figure 5 [Figure 5: see original paper] shows, P, Cl, and K respond significantly to an 417

increasing in O, n) S reaction rate. Since observa- tions of P and Cl in EMP stars are not available, we restrict comparisons to K abundance in this section.

f 16O = 0.1, 1.0, 5.0, and 10.0, alongside values reported by 422

Heger and Woosley [ ] and Limongi and Chieffi [ ]. The mean of observed [K/Ca] abundance with 1 and 2 uncer- tainties from Ishigaki et al.] are shown as the black dashed line and dark- and light-gray horizontal bands, respectively.

EMP stars provide a unique opportunity to independently test 427

the nucleosynthesis yields, since their surface compositions reflect enrichment by a few, even by an individual supernova from the Pop III massive stars [In general, [K/Ca] increases with increasing and most models with 5.0 can reproduce the observations within an uncertainty of 2 . We should also note that the predicted [K/Ca] abundance could still be affected by other

E 5 1 = 0 . 3

E 5 1 = 1 . 2

E 5 1 = 1 0

M = 1 5 M

Comparison of [K/Ca] abundance predicted by different models to the observation. The red circles, blue diamonds, green squares and cyan triangles represent the prediction in this work for the models with (ZAMS) = 15, 20, 30, and 40 M and the mass cuts are presented at = 0.1, 1.0, 5.0, and 10.0, respectively. The dashed circles, diamonds, squares, and triangles represent the prediction for the same initial masses, but a different mass cut of . The gold and orange diamonds represent the pre- diction from Limongi and Chieffi [ ] but with rotation velocity of 0 and 300 km/s, respectively. The black squares represent the prediction from Heger and Woosley [ ] with a explosion energy of erg but the initial mass of (ZAMS) = 20, 40, 80, and

100 M

. The lightblue squares are also from Heger and Woosley] with (ZAMS) = 15 but explosion energies of 1.2 and 10. The mean of observed abundances of [K/Ca] with 1 and 2 uncertainties reported in Ishigaki et al.] are shown by the black dashed line, dark gray and light gray horizontal bands. physical processes beyond the nuclear reaction rate. For each , the solid and dashed symbols represent the adoption

of M cut = M (Fe) and M cut = M 4 (near the Si/O inter- 437

face), respectively. For most models, changes in the mass cut alter the [K/Ca] abundances by less than 0.1 dex. This small sensitivity arises because most of the K and Ca in the Si shell are consumed in subsequent explosive nucleosynthesis, leaving only a fraction that can be retained in the O shell.

Although [K/Ca] abundances decrease with the increasing of

initial mass, there still exist some exceptions, for example, 444

M (ZAMS) =

40 M

and f 16O = 0.1, M (ZAMS) =

20 M

445

and f 16O = 1.0 in this study, M (ZAMS) =

15 M

from 446

Limongi and Chieffi [ ]. These exceptions may be the result of the shell merging. Carbon-oxygen (C-O) shell mergers are likely to prevent the subsequent explosive nucleosynthesis of elements such as Cl and K, thereby increasing their ejected abundances [ ]. In contrast, an O-Si shell merger would promote the consumption of these elements, reducing their presence in the ejecta. Limongi and Chieffi [ ] showed that the rotating stars also increase the [K/Ca] abundance, particu-

larly for the model with M (ZAMS) =

15 M

and v rot = 300 455

km/s, which predicts [K/Ca] in agreement with observations.

Following Heger and Woosley [ ], we also note that a lower explosion energy can also predict a higher [K/Ca], offering an additional route to reconcile models with observations.

, CO core mass, , O core mass, , and Si core mass, , are defined at the mass coordinate where (He), (C), and (O) lower than 10 . The boundary of the iron core mass, , is defined at the mass coordinate where is defined at the mass coordinate where the entropy per nucleon

and µ 4 is defined as µ 4 = d m/ M d r/ 1000 km s =4

To facilitate a direct comparison between our nucleosyn- thesis results and the observed abundance patterns of ex- tremely metal-poor stars, we calculate the integrated galac-

tic yields using the Salpeter Initial Mass Function (IMF)[57]. 464

Due to the discrete sampling of our progenitor grid, we adopt 465

a piecewise constant approximation to represent the massive star population across the 13–45 range. Specifically, the yields of the 15, 20, 30, and 40 models are utilized to characterize the mass intervals of 13–17.5, 17.5–25, 25–35,

and 35–45 M , respectively. Stars with M (ZAMS) > 45 470

are believed to collapse into BHs and are not expected to contribute to the chemical enrichment [The integrated yield for a given isotope is derived by in-

16O = 1.0 as a function of Γ under different explosion assumptions.

the IMF (1+Γ) over the total mass range:

Y i =

nario, taking a value of 1 for successful explosions and 0 for explosion failures.

Since the IMF of these Pop III stars is still uncertain, we further examine the impact of the IMF slope by varying the power-law index across values of

-0.65, 0, 1.35 (standard Salpeter), and 2.35 in Figure under different explosion as- sumptions. When increases from -0.65 to 2.35, the inte- grated [K/Ca] abundances increase by dex. Com-

pared with the impact of initial mass, rotation, explosion en- 486

ergy, and discussed in Section , this variation is not large. In the subsequent discussion, we only adopted the stan-

dard Salpeter slope of $\Gamma = 1 . 35$ 4 . 489

In Figure , the different explosion assumptions also af- fect the integrated [K/Ca].

We find that the models more likely to explode tend to yield higher [K/Ca], so excluding those collapse models raises the integrated [K/Ca]. ever, given the limited number of models, this should not be regarded as a rigorous conclusion. In addition, as shown in Figure , [K/Ca] abundance predicted by models with

M (ZAMS) =

100 M

are higher than those predicted by 497

M (ZAMS) =

20 M

in Heger and Woosley [33]. 498

4 The integrated isotopic yields of Cl, Ar, K, Ca, Ti, and Fe under dif- ferent mass cuts, explosion assumptions, and are uploaded at DOI: 10.5281/zenodo.19162071 (ZAMS)

Because the number of observed elements and the sam- ple size reported in Ishigaki et al.] are limited, especially

since no other O burning products besides K and Ca are in- 501

cluded, we further compared the IMF-integrated abundances with the observational constraints compiled by Cayrel et al.] in Figure . We find that [Sc/Ca] also increases with increasing, similar to the behavior of [K/Ca]. This is because Sc originates from radioactive decay of Ti, which

is produced in explosive O burning. When $f_{16O} \leq 5.0$, the 507

choice of explosion assumption has little impact, if the mass cut is set to , whereas it becomes important when

adopting $M_{cut} = M_4$. Consistently, we obtain that $f_{16O} =$ 510

10.0 tends to overestimate the yields of both K and Sc, while the abundance ratios [Sc/Ca] and [K/Ca] for f 16O = 5.0 fall

within the observation ranges. In the right panel, [Ti/Ca] increases by only 0.4 dex as

f 16O varies from 0.1 to 10 for M cut = M (Fe) . However, if

[K/Ca] is consistent with the observations, Ti remains under- produced. This discrepancy is expected because explosive O

burning produces only 46 , 47 Ti, whereas the dominant isotope

48 Ti originates from explosive Si burning [59]. Therefore,

if the Si burning shell is treated as part of the compact rem-

nant, then [Ti/Ca] becomes insensitive to ; instead, its abundance depends primarily on the location of . Overall, enhancing the O, n) S reaction rate by a factor of five provides a better match to the observed K and Sc abundances, although Ti is still systematically underproduced.

CONCLUSION

Motivated by the recent observational results about the enrichment of K on the surface of extremely metal-poor (EMP) stars, we systematically investigated the impact of the

16 O(

O, n) S reaction rate on the late-stage evolution and nucleosynthesis of massive Pop III stars. In this study, we

calculated the stars with M (ZAMS) = 15, 20, 30, and 40

and varies the O, n) S reaction rate by factors of 0.1, 1.0, 5.0, and 10.0.

All stellar models are evolved from the zero-age main sequence (ZAMS) to the onset of core collapse.

We then followed the explosive nucleosynthe- sis through the resulting supernova shock and calculated the

IMF-integrated abundances of O-burning products. To com-

pare our models with the previous models and observations, our study can be summarized as follows: (1) Increasing the O, n) S reaction rate by factors

of 0.1, 1.0, 5.0, and 10.0 results in slightly lower ignition tem-

peratures and slow the temperature rise. As a consequence,

the O-burning lifetime is extended. Besides, increasing this reaction rate reduces in the SiO shell, thereby affecting the yields of some odd-Z elements. However, central is almost

unchanged, since it is mainly determined by Si burning and

the NSE process. (2) Before the explosion, we find the neutron-rich isotopes, such as K, and Ca, are sensitive to this reaction rate. Particularly, the yields of P, Cl, and K are enhanced by a factor of 2.8, 2.8, and 3.8, respec-

tively. While the yields beyond O burning products may not

be sensitive to this reaction rate.

(3) To identify which progenitors contribute to chemical

enrichment, we assess their explosion outcomes using the

density-jump. Stars with M (ZAMS) = 20 exhibit a den-

sity jump near 2.3 - 2.5 M , indicating a larger and more compact core. In contrast, the density jumps of other

stellar models are concentrated near M r = 11.5 - 1.8 M .

We then quantify their explodability using log (V/U) max =

1.205 +0 . 070 − 0 . 055 . Then we find stars with M (ZAMS) = 15 and 30

successfully explode and produce ejecta, whereas stars

with M (ZAMS) = 20 and 40 M are more likely to collapse

into BHs and thus contribute little ejecta. (4) The variation in K yield is the primary focus of this study. Based on the results after the explosive nucleosynthesis calculations, we compared our results with the pre- dicted [K/Ca] abundances from different theoretical models as well as the latest observations. We find that with the de-

fault 16 O(16 O, n) 31 S reaction rate (f 16O = 1.0, [K/Ca] pre-

, respectively. The gray crosses are the observed abundances in EMP stars from Cayrel et al.

dicted by our models are higher than those reported in previ- ous works. When 5.0, the predicted [K/Ca] fall within the observational uncertainty of . Furthermore, by exam-

ining the impact of the choices of mass cut, we note that the

structures of the O- and Si-shells can significantly affect the

[K/Ca] abundance in some models. (5) To make our predictions more general, we integrate

the yields over different initial masses, accounting for vari-

ations in the mass cut, explosion assumptions, and the IMF slope.

We then compare our predicted abundance ratios-[Sc/Ca], [K/Ca], and [Ti/Ca] with the observations. Overall, we find that both [Sc/Ca] and [K/Ca] tend to increase as increases.

In particular, the predicted [Sc/Ca] and [K/Ca] ratios fall within the observational uncertainties. However, the [Ti/Ca] abundances appear to be systematically underes- timates for all considered We conclude that the enhancing the O, n) S reac-

tion rate modifies Y e near in and nearby the O burning shell, 589

thereby increasing the production of neutron-rich isotopes. In particular, the yields of the odd-Z elements, P, Cl, K, and Sc, K. Nomoto, C. Kobayashi, and N. Tominaga, Annual Review of Astronomy & Astrophysics , 457 (2013) H. Li, W. Aoki, T. Matsuno, Q. Xing, T. Suda, N. Tomi- naga, Y. Chen, S. Honda, M. N. Ishigaki, J. Shi, J. Zhao, and G. Zhao, Astrophys. J. , 147 (2022) arXiv:2203.11529 Q.-F. Xing, G. Zhao, Z.-W. Liu, A. Heger, Z.-W. Han, W. Aoki, Y.-Q. Chen, M. N. Ishigaki, H.-N. Li, and J.-K. Zhao, Nature (London) , 712 (2023) S. E. Woosley, A. Heger, and T. A. Weaver, Reviews of Modern Physics , 1015 (2002) B. Bucher, X. D. Tang, X. Fang, A. Heger, S. Almaraz-Calderon, A. Alongi, A. D. Ayangeakaa, M. Beard, A. Best, J. Browne, C. Cahillane, M. Couder, R. J. deBoer, A. Kon- tos, L. Lamm, Y. J. Li, A. Long, W. Lu, S. Lyons, M. No-

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are enhanced while those beyond O burning, for example, Ti, 592 are not sensitive to this reaction rate. By comparing with the observed abundances from EMP stars, we find that increasing this reaction rate from the CF88 compilations by a factor of 5 leads to predicted abundance ratios [K/Ca] and [Sc/Ca] that fall within the observational ranges.

It should be noted, however, that applying a single global scaling factor across all temperatures is a simplified approxi- mation; therefore, adopting the reaction rate based on recent measurements with the temperature-dependent uncertainties are crucial for obtaining reliable O-burning yields and their variations. Besides, the final yields of these odd-Z elements are also affected by shell mergers, the explosion mechanism, and the rotation effect. In future studies, it is necessary to em- ploy the updated O reaction rate with branching ratios from recent measurements. Using finer progenitor mass grids and performing systematic studies over a broader set of ex- plosion parameters will further test these trends. Finally, a larger observation sample, which includes P, Cl, K, and Sc, will provide stronger constraints on our results.

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