EMPRESS. VIII. A New Determination of Primordial He Abundance with Extremely Metal-poor Galaxies: A Suggestion of the Lepton Asymmetry and Implications for the Hubble Tension

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Abstract

The primordial He abundance Yp is a powerful probe of cosmology. Currently, Yp is best determined by observations of metal-poor galaxies, while there are only a few known local extremely metal-poor (<0.1 Z⊙) galaxies (EMPGs) having reliable He/H measurements with He1λ10830 near-infrared (NIR) emission. Here we present deep Subaru NIR spectroscopy for 10 EMPGs. Combining the existing optical data, He/H values of 5 out of the 10 EMPGs are reliably derived by the Markov chain Monte Carlo algorithm. Adding the existing 3 EMPGs and 51 moderately metal-poor (0.1–0.4 Z⊙) galaxies with reliable He/H estimates, we obtain Yp = 0.2370 ± 0.0033 by linear regression in the (He/H)–(O/H) plane, where we increase the number of EMPGs from three to eight anchoring He/H of the most metal-poor gas in galaxies. Although our Yp measurement and previous measurements are consistent, our result is slightly (~1σ) smaller due to our EMPGs. Including the existing primordial deuterium D measurement, we constrain the effective number of neutrino species Neff and the baryon-to-photon ratio η showing ≥1–2σ tensions with the Standard Model and Planck Collaboration et al. (2020). Motivated by the...
tensions, we allow the degeneracy parameter of the electron neutrino $\xi$, as well as $N_{\text{eff}}$ and $\eta$, to vary. We obtain $\xi = 0.05^{+0.03}_{-0.02}$, $N_{\text{eff}} = 3.11^{+0.34}_{-0.31}$, and $\eta \times 10^{10} = 6.08^{+0.06}_{-0.06}$ from the $Y_P$ and $D_p$ measurements with a prior of $\eta$ taken from Planck Collaboration et al. Our constraints suggest a lepton asymmetry and allow for a high value of $N_{\text{eff}}$ within the 1σ level, which could mitigate the Hubble tension.

**Unified Astronomy Thesaurus concepts:** Galaxy abundances (574); Galaxy chemical evolution (580); Cosmological parameters (339); Big Bang nucleosynthesis (151)

1. Introduction

The flat $\Lambda$CDM model shows good consistency with the independent observational measurements of the cosmic microwave background (CMB; Planck Collaboration et al. 2020), the large-scale structures, and the expansion history of the universe. However, as the precision of observations increases, a significant discrepancy between the determinations of the Hubble parameter ($H_0$) is revealed. For example, Riess et al. (2019) demonstrate that the value of the direct $H_0$ measurement with 70 Cepheids is higher with 4.4σ tension than the value inferred from the Planck measurements with the $\Lambda$CDM model. This tension is called “Hubble tension”, and recent studies claim $\gtrsim 5\sigma$ differences (Wong et al. 2020; Riess et al. 2022).

The Hubble tension may be interpreted as evidence for new cosmological features beyond the $\Lambda$CDM model (e.g., Renk et al. 2017; Khostovan et al. 2019; Dainotti et al. 2021, 2022). One possible way of resolving the Hubble tension problem is to allow the effective number of neutrino species $N_{\text{eff}}$, which can be regarded as a parameter for the total energy density of relativistic particles, to change. A value of $N_{\text{eff}}$ larger than the one predicted by the Standard Model, 3.046, increases the $H_0$ value inferred from the Planck CMB observations in the $\Lambda$CDM model, reducing the scale of the sound horizon. Bernal et al. (2016) claim that $N_{\text{eff}} \sim 3.4$ can ameliorate the Hubble tension. Similarly, Vagnozzi (2020) shows that the Hubble tension would be reduced to 1.5σ by models with $N_{\text{eff}} \approx 3.45$, and these models are only weakly disfavored compared with the standard $\Lambda$CDM model.

Besides the Hubble tension, the determination of the value of $N_{\text{eff}}$ is important in particle physics and cosmology. Many particle physics beyond the Standard Model and inflation models predict the existence of extra radiation like dark radiation and gravitational waves (e.g., Dunsby et al. 2020). Because $N_{\text{eff}}$ changes from 3.046 with the presence of such extra radiations, the measurement of $N_{\text{eff}}$ places constraints on the extended models. Around the epoch of the Big Bang nucleosynthesis (BBN; see, e.g., Steigman 2007; Iocco et al. 2009, for reviews), the radiation energy density (i.e., $N_{\text{eff}}$) primarily determines the expansion rate of the universe via the Friedmann equation. The competition between the expansion rate and the weak interaction rate determines the “freeze-out” value of the neutron-to-proton abundance ratio. The neutron abundance is then reduced by free decay until BBN occurs. As virtually all remaining neutrons are processed into $^4$He (hereafter He), the primordial He abundance in the mass fraction, $Y_P$, offers a strong constraint on $N_{\text{eff}}$.

Although the CMB measurements of Planck Collaboration et al. (2020) provide $Y_P = 0.246 \pm 0.035$ (95%), this accuracy is not good enough to determine $N_{\text{eff}}$ with an uncertainty less than $\Delta N_{\text{eff}} \approx 0.6$. The $Y_P$ value can be more strongly constrained by observations for He abundances of metal-poor galaxies (i.e., galaxies whose elemental compositions are close to the primordial one), reaching subpercent level accuracy (Izotov et al. 2014; Aver et al. 2015; Peimbert et al. 2016; Fernández et al. 2019; Valeri et al. 2019; Hsyu et al. 2020; Kurichin et al. 2021). To derive He abundances of metal-poor galaxies for $Y_P$ determination, one needs to constrain the physical parameters of the ionized nebulae of the galaxies (e.g., metallicity, electron density, and ionization parameter) with observed emission lines by comparisons of photoionization models. Because it is known that optical emission lines do not allow us to resolve the degeneracy between the electron density and temperature of the nebula, the near-infrared (NIR) HeI λ10830 line, which is sensitive to the electron density, is key to removing systematic uncertainties raised by the degeneracy (Izotov et al. 2014; Aver et al. 2015). A recent study of metal-poor galaxies (Hsyu et al. 2020) uses a moderately large sample of 54 metal-poor galaxies across a metallicity range of $\langle O/H \rangle \times 10^{10} = 1.73-16.64$, some of which include HeI λ10830 measurements, and report $Y_P = 0.2436_{-0.0036}^{+0.0036}$. Hsyu et al. (2020) obtain $N_{\text{eff}} = 2.85_{-0.25}^{+0.28}$, combining the value of $Y_P$ with the measurement of the primordial D-to-H abundance ratio $D_P$ presented in Cooke et al. (2018). While the best-estimated value, $N_{\text{eff}} = 2.85_{-0.25}^{+0.28}$, is lower than $N_{\text{eff}} = 3.046$, this estimation allows $N_{\text{eff}} = 3.4$ within 2σ. The uncertainty is not small enough to test whether $N_{\text{eff}}$ can be as large as the one alleviating the Hubble tension. Although the number of the available metal-poor galaxies with reliable He abundance measurements are moderately large, ~50, in the previous study (Hsyu et al. 2020), the previous study could use only three galaxies of the low-metallicity end, extremely metal-poor-galaxies (EMPGs) with metallicities less than 10% solar oxygen abundance, where the definition of the solar metallicity is given by $12 + \log (O/H) = 8.69$ (Ashpland et al. 2009). Because EMPGs possess gas of nebulae whose He abundance is much similar to the primordial He abundance compared to more metal-enriched galaxies with a >10% solar oxygen abundance, adding EMPGs to the sample would strongly impact on the determination of primordial He abundance.

Kojima et al. (2020) have initiated a new EMP survey named “Extremely Metal-Poor Representatives Explored by the Subaru Survey (EMPRESS)”. Having successful results of EMPRESS (Kojima et al. 2020, 2021; Isobe et al. 2021, 2022; Nakajima et al. 2022; Xu et al. 2022; Umeda et al. 2022), we have launched an extended project, EMPRESS 3D (PI: M. Ouchi) that perform optical integral-field spectroscopy (IFS) and Y - band spectroscopy for ~30 EMPGs. The EMPRESS 3D project will provide deep optical spectra via the IFS data cube and weak emission lines including HeI λ10830 at the EMPG luminosity peaks. The goals of this study are to determine $Y_P$ with a high accuracy on the basis of a galaxy sample including a significantly large number of EMPGs and to evaluate $N_{\text{eff}}$ that may solve the Hubble tension. The structure of this paper is as follows. In Section 2, we present our galaxy sample. In Section 3, our observations and data reduction are described. We explain the data analysis and He abundance measurements of the observed galaxies in Section 4. In Section 5, we present our determination of $Y_P$ by the linear-regression method. In Section 6, we discuss the possibility of
new physics beyond the standard model of cosmology. Section 7 summarizes our results.

2. Sample and Data

We use a total of 64 galaxies, including 13 EMPGs, which have optical line measurements necessary for the He abundance determinations. Our sample of 64 galaxies consists of the 10 galaxies whose NIR spectra are taken by our Subaru observations (Section 2.1) and 54 galaxies from a sample of a previous study (Section 2.2). In this paper, the 10 and 54 galaxies are referred to as “Subaru galaxies” and “literature galaxies”, respectively.

2.1. Subaru Galaxies

We select the Subaru galaxies from the known EMPGs whose He abundance has not been determined from NIR data. We choose 11 galaxies, classified as EMPGs, with (O/H) = 1%−10% solar abundances reported in previous studies (Thuan & Izotov 2005; Papaderos et al. 2008; Izotov et al. 2012, 2019; Kojima et al. 2020; Nakajima et al. 2022; Xu et al. 2022), which are bright and visible in our observing runs in January, February, April, May, and July. The Subaru galaxies are summarized in Table 1.

2.2. Literature Galaxies

For the literature galaxies, we use 54 galaxies, 8 of which have the NIR spectroscopic data. These 54 galaxies are taken from Sample 1 of Hsyu et al. (2020), which is a sample with reliable HI and He I emission modeling. In the literature galaxies, 3 out of 54 galaxies are EMPGs. The addition of the Subaru galaxies more than quadruples the number of EMPGs for the Yp determination in the previous study.

3. Near-infrared Spectroscopy and Data Reduction

We observed the Subaru galaxies with three NIR spectrographs on the Subaru telescope, Multi-Object Infrared Camera and Spectrograph (MOIRCS; Ichikawa et al. 2006; Suzuki et al. 2008), Infrared Camera and Spectrograph (IRCS; Tokunaga et al. 1998; Kobayashi et al. 2000), and Simultaneous-color Wide-field Infrared Multi-object Spectrograph (SWIMS; Motohara et al. 2014, 2016; Konishi et al. 2018, 2020). These observations are summarized in Table 2.

3.1. MOIRCS

3.1.1. MOIRCS Observations

The NIR spectroscopy for one of the Subaru galaxies, J1631+4426, was conducted using MOIRCS on the date of 2020 July 23 with the z/500 grism and a 0.6″ wide long slit, yielding spectra spanning 0.9–1.78 μm. The resolving power was R ≈ 300. Dome flats were obtained at the beginning of the night. We moved the telescope in an AB dithering pattern with a total exposure time of 1800 s. We took the spectrum of a standard star, HIP89634, for our flux calibration.

3.1.2. MOIRCS Data Reduction

Data reduction is performed with the IRAF package. The reduction and calibration processes include flat-fielding, cosmic-ray cleaning, wavelength calibration, background subtraction, and combining the nod positions before one-dimensional spectrum extraction. Wavelength solutions for MOIRCS spectra are obtained from the ThAr lamp. We then extract one-dimensional spectra and calibrate the fluxes. We extract one-dimensional spectra with a boxcar aperture that encompasses roughly 99% of the emission. We extract the error spectra considering the read-out noise and photon noise of sky and object emission, and the uncertainty of the flux calibrations. The last source of the error is accounted for assuming a 2% relative flux uncertainty based on observations of standard stars (Oke 1990). Figure 1 shows the one-dimensional spectra taken with MOIRCS.

| ID (1) | R.A. (2) | Decl. (3) | z (4) | Reference for Optical Spectra (5) |
|-------|---------|-----------|------|----------------------------------|
| J1631+4426 | 247.8093333 | 44.4345639 | 0.0230 | Kojima et al. (2020) |
| J1418+3752 | 214.7130000 | 21.0443722 | 0.0090 | Xu et al. (2022) |
| J1016+3754 | 154.1022083 | 37.9127694 | 0.0039 | SDSS |
| I Zw 18 NW | 143.5084380 | 55.2411310 | 0.0024 | Thuan & Izotov (2005) |
| J1201+0211 | 180.3430000 | 2.1856900 | 0.0030 | SDSS |
| J1119+5130 | 169.8930000 | 51.5034000 | 0.0020 | SDSS |
| J1234+3901 | 188.5654170 | 39.0212250 | 0.13297 | SDSS |
| J0133+1342 | 23.4690000 | 13.7026000 | 0.00879 | SDSS |
| J0825+3532 | 126.4810000 | 35.5422000 | 0.0020 | SDSS |
| J0125+0759 | 21.3924567 | 7.9901917 | 0.0100 | Nakajima et al. (2022) |
| J0935-0115 | 143.9133478 | −1.2615025 | 0.0162 | Nakajima et al. (2022) |

Note. (1): ID. (2): R.A. (3): decl. (4): Redshift. (5): Reference for optical spectra.

| ID (1) | Instrument (2) | Exposure Time (s) (3) | Seeing (arcsec) (4) | Observation Date (5) |
|-------|----------------|----------------------|---------------------|---------------------|
| J1631+4426 | MOIRCS | 3600 | 0.6 | 2020 July 23 |
| J1418+3752 | IRCS | 1200 | 0.9 | 2021 March 31 |
| J1016+3754 | IRCS | 1200 | 0.9 | 2021 March 31 |
| I Zw 18 NW | SWIMS | 1200 | 0.4 | 2021 May 28 |
| J1201+0211 | SWIMS | 1200 | 0.4 | 2021 May 28 |
| J1119+5130 | SWIMS | 1200 | 0.4 | 2021 May 28 |
| J1234+3901 | SWIMS | 1200 | 0.4 | 2021 May 28 |
| J0133+1342 | SWIMS | 1200 | 0.4 | 2022 January 12 |
| J0825+3532 | SWIMS | 1800 | 0.4 | 2022 January 12 |
| J0125+0759 | SWIMS | 1800 | 0.4 | 2022 January 12 |
| J0935-0115 | SWIMS | 720 | 0.4 | 2022 February 8 |

Note. (1): ID. (2): Instruments for our NIR spectroscopy. (3): Total exposure time. (4): FWHM of the seeing size. (5): Date of our NIR spectroscopy.
3.2. IRCS

3.2.1. IRCS Observations

We carried out NIR spectroscopy for two of Subaru galaxies J1418+2102 and J1016+3754 with IRCS on 2021 March 31.30 We used the zJ grism with a 52 mas pixel scale with an observed-wavelength coverage of approximately 1.03–1.18 μm. A spectral resolution of $R \approx 300$ was accomplished with a 0.6" wide long slit. We took dome flats at the beginning of the night. We performed ABBA dithering with an individual exposure of 300 s. We observed an A0V Hipparcos star, HIP68868, at an airmass similar to those of our targets for flux calibration.

3.2.2. IRCS Data Reduction

The IRCS spectra and the error spectra are processed in the same manner as the MOIRCS spectrum. Note that the emission lines of the IRCS spectra have profiles similar to box shapes due to the spatially extended objects observed with a large slit width for IRCS, while this does not affect the flux measurements by summing the pixels above the continuum.

Figure 1. Rest-frame spectra of Subaru galaxies, taken with IRCS, SWIMS, and MOIRCS. The blue lines and red lines present the fluxes and the 1σ errors, respectively. Note that the emission lines of the IRCS spectra have profiles similar to box shapes due to the spatially extended objects observed with a large slit width for IRCS, while this does not affect the flux measurements by summing the pixels above the continuum.

30 Although we observed galaxy J1253-0312 with IRCS, after the IRCS observations we recognized that J1253-0312 was not classified as an EMPG, which had an oxygen abundance of 25% the solar abundance.
lines of the IRCS spectra have profiles similar to rectangular shapes (see Figure 1). This is because we observed spatially extended objects with a large slit width for the IRCS instrument. The IRCS spectra are convolutions of the instrumental profile with a box shape of the slit. These spectral shapes are commonly found in the IRCS spectra for the similarly extended targets and the observational configuration, though line flux measurements are not affected.

3.3. SWIMS

3.3.1. SWIMS Observations

We conducted NIR spectroscopy with SWIMS for eight of the Subaru galaxies, I Zw 18 NW, J1201+0211, J1119+5130, and J1234+3901 on 2021 May 28; J0133+1342, J0825+3532, and J0125+0759 on 2022 January 12; and J0935-0115 on 2022 February 8. We utilized the multiobject spectroscopy mode and long-slit spectroscopy mode for J0125+0759 and the other galaxies, respectively. The \( c \) and \( HK \) grisms were used with the blue and red channels, respectively, with the dichroic at 1.4 \( \mu m \), resulting in an observed-wavelength coverage of approximately 0.9–2.5 \( \mu m \). With a slit width of 0.8", the spectral resolutions were \( R \approx 700–1200 \) and 600–1000 in the blue and red channels, respectively. Dome flats were obtained at the beginning of the nights. We used an ABBA dither pattern with individual exposures of 300 s for the targets except for J0125+0759. The individual exposure time was 180 s for J0125+0759. For flux calibration, AOV Hipparcos stars, HIP59861, HIP116886, and HIP19578 were observed at an airmass similar to the one of our targets on the dates of 2021 May 28, 2022 January 12, and 2022 February 8 respectively.

3.3.2. SWIMS Data Reduction

We reduce the SWIMS spectra and the error spectra in the same manner as the MOIRCS and IRCS data reduction. Because the second spectrum obtained at nod location B of each ABBA dither on 2021 May 28 includes systematic uncertainties due to a SWIMS instrument problem, we remove their second spectra in the ABBA dither data sets. We obtain wavelength solutions for the SWIMS spectra from OH sky lines. The reduced SWIMS spectra are presented in Figure 1.

4. Analyses

4.1. Flux and EW Measurements

We measure the hydrogen, helium, oxygen, and sulfur emission line fluxes. While the different instruments are used for the optical and NIR spectroscopy, we assume that the same region of each galaxy was observed. Under this assumption, the difference in aperture does not affect our analysis because we measure the ratios of the optical (NIR) line fluxes to H\( \beta \) (P\( ^{\gamma} \)) fluxes to avoid systematics caused by the different amount of slit loss fluxes.

4.1.1. Optical Spectra

We use the optical spectra and the corresponding error spectra of Magellan/MagE, Keck Deep Imaging Multiobject Spectrograph, and the Sloan Digital Sky Survey (SDSS) for the Subaru galaxies obtained by previous observations (see Table 1) for our optical line measurements. The exception is I Zw 18 NW, for which we use the emission line flux values reported in Thuan & Izotov (2005) with higher precision than that of the SDSS spectrum. For the Subaru galaxies except for I Zw 18 NW, we define the continuum by fitting a polynomial of degree 3 to the range that is deemed by visual inspection to be free of any emission and absorption lines. After subtraction of the continuum from the spectra, we measure the line fluxes and EWs of optical emission lines [OII]\( \lambda 3727 \), He I\( \lambda 3889 \), He I\( \lambda 4026 \), [OIII]\( \lambda 4363 \), He I\( \lambda 4641 \), He I\( \lambda 4686 \), [OIII]\( \lambda 5007 \), He I\( \lambda 5876 \), He I\( \lambda 6678 \), [SII]\( \lambda 6717 \), [SII]\( \lambda 6731 \), He I\( \lambda 7065 \), [OIII]\( \lambda 7320 \), [OIII]\( \lambda 7330 \), [SIII]\( \lambda 9069 \); the Balmer series from H\( \alpha \) to H\( \delta \); and the blended H\( \beta \)+He I\( \lambda 3889 \). However, there are residual offsets around some emission lines in the continuum-subtracted spectra, which introduces systematic uncertainties in the flux measurements. These residual offsets cannot be defined by fitting constants to the regions around the emission lines because some of the emission lines with other nearby emission lines or the stellar absorption do not have surrounding flat regions wide enough to define the offsets. As such, we simultaneously fit a Gaussian and a constant to each emission line in the continuum-subtracted spectra, where we exclude the nonflat regions around the emission lines from the fitting ranges. In this consistent manner, for all emission lines, we measure the line fluxes with the Gaussian profiles correcting for the residual offsets with the constants. The fluxes of the blended lines are calculated by fitting a double Gaussian, except for the blended H\( \beta \)+He I\( \lambda 3889 \), whose profiles are well fit by a single Gaussian. To fit the continuum and the emission lines, we use the scipy.optimize package, which employs a \( \chi^2 \) minimization approach considering the error spectra. In the error spectra from Kojima et al. (2020), Nakajima et al. (2022), and Xu et al. (2022), for which the flux calibration was performed with only one standard star, we include the 2\% relative flux uncertainty of standard stars (Oke 1990). The error of the emission line fluxes are calculated from uncertainties of the Gaussian fit. As one-dimensional spectra are binned by a pixel of a resolution element, the correct method of the Gaussian fit is to bin the fitting function by a pixel before fitting to the spectrum. In our optical flux measurements, however, we fit unbinned Gaussian profiles to the spectra for simplicity assuming that the choice of the fitting methods does not affect our result. We have confirmed this assumption comparing both cases of the fitting methods for one of the Subaru galaxies, J1201+0211. As we expect, the line fluxes of J1201+0211 derived by these two methods are virtually indistinguishable. For example, the H\( \beta \) fluxes in units of \( 10^{-16} \) erg s\(^{-1} \) cm\(^{-2} \) obtained by the Gaussian fitting with binning and without binning are 116.394 ± 1.692 and 116.388 ± 1.729, respectively.

The exception is J1418+3752, whose emission line fluxes have broader profiles due to outflows. Because the emission lines of J1418+3752 cannot be fit with a single Gaussian, we exclude this galaxy for our \( Y_p \) determination.

We also measure the line fluxes by summing the pixels above the continuum level (hereafter referred to as the integration method), but the residual offsets in the continuum-subtracted spectra introduce systematic uncertainties to the optical line flux values. We therefore adopt line fluxes measured by a Gaussian fit for the optical spectra. In Sections 4.2.2 and 5.1, we discuss the impact of our choice of the methods for the line flux measurements on our result.
4.1.2. Near-infrared Spectra

Because the emission lines of MOIRCS, SWIMS, and IRCs spectra, unlike those of the optical spectra, are not well represented by a single Gaussian (see Figure 1), the fluxes of these lines are derived by summing the pixels above the continuum determined in the same manner as the optical flux measurements, where there are no obvious residual offsets from the defined continuum of the NIK spectra. We estimate the line flux errors propagating the uncertainty of the continuum level to the error spectra. We show the derived flux ratios and equivalent widths of the HeI\(\lambda 10830\) emission line of the Subaru galaxies in Table 3.

4.2. He Abundance

We assume that almost all hydrogen atoms are ionized in the region considered in this paper. Therefore, the abundance ratio of helium to hydrogen is given by the sum of the abundance ratios of neutral \(y^0\), singly ionized \(y^+\), and doubly ionized \(y^{++}\) helium to ionized hydrogen.

\[
y = y^{++} + y^+ + y^0.
\]

We derive the \(y\) values of the Subaru galaxies described in Section 2.1, following the procedures similar to those of Hsyu et al. (2020). The \(y^{++}\) value is calculated with the He II\(\lambda 4686\) line flux. The \(y^+\) value is derived based on the Markov chain Monte Carlo (MCMC) analysis with multiple He I and HI lines. We then check the contribution of the neutral He abundance to the \(y\) value. We describe the details in Sections 4.2.1, 4.2.2, and 4.2.3 below. The derived \(y\) values are listed in Table 4.

4.2.1. Doubly Ionized Helium Abundance Ratios

We estimate the \(y^{++}\) values with line flux ratios of He II\(\lambda 4686\) to H\(\beta\) with Equation (17) of Pagel et al. (1992):

\[
y^{++} = 0.084 t(\text{O III})^{1.14} \frac{F(\text{He II}\lambda 4686)}{F(\text{H}\beta)},
\]

where \(t(\text{O III})\) is the electron temperature in units of 10\(^5\) K in the doubly ionized oxygen region. We use reported values of \(t(\text{O III})\) (Thuan & Izotov 2005; Papaderos et al. 2008; Izotov et al. 2012, 2019; Kojima et al. 2020). If there is no detectable He II\(\lambda 4686\) line in a galaxy, the \(y^{++}\) abundance of the galaxy is assumed to be negligible. The \(y^{++}\) values of the Subaru galaxies are listed in Table 5.

4.2.2. Singly Ionized Helium Abundance Ratios

We determine the \(y^+\) values of each galaxy using the YMCMC code developed by Hsyu et al. (2020). Exploiting the MCMC algorithm, the YMCMC code conducts model fitting to the observed emission line ratios among He I\(\lambda 3889\), He I\(\lambda 4471\), He I\(\lambda 5015\), He I\(\lambda 5876\), He I\(\lambda 6678\), He I\(\lambda 7065\), the Balmer series from H\(\alpha\) to H\(\beta\), He I\(\lambda 10830\), and P\(\gamma\) to constrain eight free parameters, \(y^+, T_e, n_e, c(H/\beta), a_{HI}, a_{He I}, a_{He II}, \tau_{He I}\), and \(\xi\) with 68% errors. \(T_e\) [K] is the electron temperature, \(n_e\) [cm\(^{-3}\)] is the electron density, \(c(H/\beta)\) is the parameter of the correction for reddening, \(a_{HI}\) [Å] is the hydrogen stellar absorption normalized to that at H\(\beta\), \(a_{He I}\) [Å] is the helium stellar absorption normalized to the value at He I\(\lambda 4471\), \(\tau_{He I}\) is the helium optical depth normalized to the value at He I\(\lambda 3889\), and \(\xi\) is the ratio of the number density of the neutral to singly ionized hydrogen. Here, we use 500 walkers, 1000 steps, and a burn-in of 800 steps without thinning, following the procedure of Hsyu et al. (2020). For I Zw 18 NW, we do not employ the He I\(\lambda 5876\) in the analysis though its line flux ratio is reported in Thuan & Izotov (2005) because it is blended with Galactic interstellar sodium absorption (Izotov et al. 1999).

In the YMCMC analysis, we assume that the observed flux ratios arise from corresponding "true" flux ratios, and thus the best-recovered parameters are scattered from the "true" parameter values that reproduce the "true" flux ratios. For example, if the "true" values of \(c(H/\beta), a_{HI}, a_{He I},\) and \(\tau_{He I}\) which cannot originally be negative, are positive but close to zero, their best-fit values that reproduce the observed flux ratios can be negative. In this case, the expectation values of the estimated parameters, which we obtain by restricting \(c(H/\beta), a_{HI}, a_{He I},\) and \(\tau_{He I}\) to be positive, can be different from the "true" values, while those extending prior boundaries can be equal to the "true" values.

To confirm the effects of the prior ranges on the expectation values of the recovered parameters, we compare simulations of the YMCMC analysis obtained in two different ways:

---

### Table 3

| ID          | \(F(\text{HeI}\lambda 10830)/F(P\gamma)\) | EW (Å)     |
|-------------|-------------------------------------------|------------|
| J1631+4426  | 1.29 ± 0.28                               | 144.1 ± 21.1 |
| J1016+3754  | 2.18 ± 0.13                               | 103.0 ± 3.6 |
| I Zw 18 NW  | 2.18 ± 0.11                               | 108.8 ± 5.2 |
| J1201-0211  | 7.90 ± 0.36                               | 1108.6 ± 82.4 |
| J1119+5130  | 2.02 ± 0.16                               | 44.0 ± 2.4  |
| J1234+3901  | 5.83 ± 0.89                               | 868.1 ± 406.0 |
| J0133+1342  | 4.05 ± 0.26                               | 364.4 ± 27.8 |
| J0825+3532  | 2.80 ± 0.10                               | 790.5 ± 96.8 |
| J0125+0759  | 4.21 ± 0.27                               | 631.0 ± 51.2 |
| J0935-0115  | 5.45 ± 0.55                               | 3915.3 ± 3485.3 |

**Note.** (1): ID. (2): Flux ratio of He I\(\lambda 10830\) to P\(\gamma\). (3): Equivalent width of the He I\(\lambda 10830\) emission line.

### Table 4

| ID          | \(y\) | \(O/H\times10^3\) (Reference) |
|-------------|------|-----------------------------|
| J1631+4426  | 0.0617 ± 0.0031 | 0.79 ± 0.06 (Kojima et al. 2020) |
| J1016+3754  | 0.0779 ± 0.0045 | 4.37 ± 0.10 (Izotov et al. 2012) |
| I Zw 18 NW  | 0.0703 ± 0.0032 | 2.18 ± 0.04 (Thuan & Izotov 2005) |
| J1201-0211  | 0.0677 ± 0.0063 | 3.12 ± 0.11 (Papaderos et al. 2008) |
| J1119+5130  | 0.0816 ± 0.0043 | 3.20 ± 0.17 (Izotov et al. 2012) |
| J1234+3901  | 0.0804 ± 0.0019 | 1.09 ± 0.07 (Izotov et al. 2019) |
| J0133+1342  | 0.0777 ± 0.0005 | 3.64 ± 0.11 (Papaderos et al. 2008) |
| J0825+3532  | 0.0544 ± 0.0048 | 2.86 ± 0.08 (Thuan & Izotov 2005) |
| J0125+0759  | 0.0935 ± 0.0003 | 4.47 ± 0.19 (Nakajima et al. 2022) |
| J0935-0115  | 0.0685 ± 0.0003 | 1.49 ± 0.22 (Nakajima et al. 2022) |

**Note.** (1): ID. (2): Abundance ratio of helium to hydrogen (Equation (1)). (3): Abundance ratio of oxygen to hydrogen used and its reference.
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Table 5

Physical Properties of the Subaru Galaxies

| ID          | Te (K) | log_c(n_e) | c(Hβ) | a_H | a_He | η_He | log(ξ) | y^+ | y^++ | η_He |
|-------------|--------|------------|-------|-----|------|-------|--------|-----|------|-------|
| J1631+4426  | 24990  | -1.30 ± 0.80 | -0.61 ± 0.04 | 6.46 ± 1.15 | 0.06 ± 0.44 | -5.38 ± 2.97 | -6.9 ± 2.1 | 0.0596 ± 0.0102 | 0.0020 ± 0.0004 | 0.12 ± 0.19 |
| J1016+3754  | 18400  | -0.79 ± 0.53 | 0.120 ± 0.024 | -1.20 ± 0.56 | 0.14 ± 0.11 | 0.15 ± 0.50 | -6.0 ± 2.7 | 0.0761 ± 0.0027 | 0.0017 ± 0.0002 | 0.26 ± 0.04 |
| I Zw 18 NW  | 20610  | 1.34 ± 0.26 | 0.111 ± 0.022 | -0.19 ± 0.43 | 0.14 ± 0.05 | -0.79 ± 0.96 | -6.5 ± 2.4 | 0.0671 ± 0.0032 | 0.0003 ± 0.0001 | 0.40 ± 0.23 |
| J1201+0211  | 17560  | 2.93 ± 0.10 | 0.272 ± 0.059 | -5.62 ± 3.19 | 0.05 ± 0.47 | 2.20 ± 0.63 | -5.3 ± 3.2 | 0.0668 ± 0.0064 | 0.0009 ± 0.0003 | 0.85 ± 0.10 |
| J1119+5130  | 14970  | -1.13 ± 0.45 | 0.178 ± 0.040 | -0.35 ± 0.36 | 0.17 ± 0.12 | -0.68 ± 0.89 | -5.9 ± 3.0 | 0.0794 ± 0.0040 | 0.0017 ± 0.0005 | 0.55 ± 0.08 |
| J1234+3901  | 21810  | 2.43 ± 0.07 | 0.153 ± 0.009 | -3.55 ± 3.48 | -0.01 ± 0.25 | 4.14 ± 2.80 | -6.1 ± 2.6 | 0.0770 ± 0.0016 | 0.0034 ± 0.0015 | -0.65 ± 0.02 |
| J0133+1344  | 18030  | 2.28 ± 0.16 | 0.382 ± 0.019 | -0.58 ± 0.58 | 1.20 ± 0.81 | -1.81 ± 0.74 | -6.4 ± 2.5 | 0.0765 ± 0.0056 | 0.0012 ± 0.0003 | 0.40 ± 0.07 |
| J0825+3532  | 18760  | 2.24 ± 0.17 | 0.374 ± 0.140 | -5.16 ± 2.62 | -1.66 ± 0.47 | 0.03 ± 0.49 | -4.9 ± 3.4 | 0.0544 ± 0.0048 | 0.0003 ± 0.0012 | 0.45 ± 0.02 |
| J0125+0759  | 21610  | 1.89 ± 0.19 | 0.353 ± 0.017 | 18.53 ± 2.84 | 8.09 ± 1.26 | -0.74 ± 0.49 | -6.8 ± 2.2 | 0.0945 ± 0.0045 | 0.0003 ± 0.0003 | 0.16 ± 0.11 |
| J0935-1157  | 19200  | 2.57 ± 0.14 | 0.199 ± 0.013 | 7.48 ± 1.08 | 0.92 ± 0.45 | -0.81 ± 0.40 | -6.6 ± 1.3 | 0.0667 ± 0.0005 | 0.0020 ± 0.0002 | 0.24 ± 0.09 |

Notes. (1): ID. (2)–(9): Properties determined with the YMCMC code (Section 4.2.2). (10): Doubly ionized He abundance (Section 4.2.1). (11): Radiation softness parameter (Section 4.2.3).

Galaxies that do not meet the χ^2_{YMCMC} criterion (Section 4.2.2).

(X) with the flat priors of

\begin{align*}
0.06 & \leq y^+ \leq 0.10 \\
0 & \leq \log_{10}(n_e) \leq 3 \\
0 & \leq c(H\beta) \leq 0.5 \\
0 & \leq \alpha_{H} \leq 10 \\
0 & \leq \alpha_{He} \leq 4 \\
0 & \leq \eta_{He} \leq 5 \\
-6 & \leq \log_{10}(\xi) \leq -0.0969
\end{align*}

used in Hsyu et al. (2020);

(Y) with the flat priors of

\begin{align*}
0.01 & \leq y^+ \leq 0.15 \\
0 & \leq \log_{10}(n_e) \leq 5 \\
-1 & \leq c(H\beta) \leq 2 \\
-10 & \leq \alpha_{H} \leq 10 \\
-5 & \leq \alpha_{He} \leq 5 \\
-7 & \leq \eta_{He} \leq 8 \\
-10 & \leq \log_{10}(\xi) \leq 0.5
\end{align*}

whose ranges are wide enough for this simulation to reveal the overall shapes of the probability distribution functions that are not distorted by the prior boundaries.

While the values of c(Hβ), \alpha_{H}, \alpha_{He}, and \eta_{He} are restricted to be positive in case (X), they are allowed to be negative in case (Y). We generate mock “true” flux ratios by making use of the YMCMC code, in which the flux ratios are predicted given the eight physical parameters. Here, we set the “true” parameter values of y^+ = 0.080, log_{10}n_e = 2.5, c(Hβ) = 0.2, a_H = 0.1, a_He = 0.1, \eta_He = 1, \log_{10}(\xi) = -5, and T_e = 18000 to generate the mock “true” flux ratios. Note that the “true” values of a_H, a_He, and c(Hβ) are close to the lower bounds of the flat priors in case (X), a_H > 0, a_He > 0, and c(Hβ) > 0. The EW values of these fluxes, needed to run the YMCMC code, are also set. The mock flux ratios and EWs are listed in Table 6.

Then, 1000 sets of mock “observed” fluxes are drawn from Gaussian distributions with central values of the mock “true” fluxes and scatter of 5% of the central values. For each set of the mock “observed” fluxes, we derive the best-fit parameters using the YMCMC code in both cases (X) and (Y). In Figure 2, we show histograms for the distributions of the best-fit values of y^+, c(Hβ), \alpha_{H}, \alpha_{He}, and \eta_{He} for each set of “observed” flux ratios in cases (X) and (Y). While the best-recovered values in case (X) are systematically affected, those in case (Y) are distributed around the “true” value. Because our linear regression in Section 5.1 assumes that the expectation values of the derived He/H values of galaxies are equal to their true He/H values, we extend the flat prior ranges from those of Hsyu et al. (2020) in our YMCMC analysis to prevent the parameters from being pushed up against the prior boundaries as best as possible.

Using the YMCMC code, we obtain the best-fit parameters for the Subaru galaxies and present these values in Table 5. As an example, we show contours and histograms for the recovered model parameters of J1201+0211 in Figure 3.

To identify the galaxies whose parameters are reliably determined, for each galaxy we calculate the χ^2_{YMCMC} value given by

\begin{equation}
\chi^2_{YMCMC} = \sum_{\lambda} \left( \frac{\log_{10}(F(\lambda)_{true}) - \log_{10}(F(\lambda)_{mod})}{\sigma(\lambda)^2} \right)^2.
\end{equation}
where $F(\lambda)/F(H\beta)$ and $\sigma(\lambda)$ are the line flux ratio and its uncertainty at wavelength $\lambda$. The subscripts obs and mod represent the observational flux ratios and the model flux ratios, respectively, with the best-fit parameters derived by the YMCMC code. The $\chi^2_{\text{YMCMC}}$ value is assumed to follow the $\chi^2$-distribution with $n_\lambda - n_{\text{param}}$ degrees of freedom, where $n_\lambda$ and $n_{\text{param}}$ are the number of the measured emission lines and that of the properties recovered by the YMCMC code (i.e., eight), respectively. We require that the model flux ratios with the eight best-fit parameters are consistent with the observed flux ratios within the 95% confidence level. Among the Subaru galaxies, five galaxies, J1016+3754, I Zw 18 NW, J1201+0211, J1119+5130, and J1234+3901, qualify via the $\chi^2$-criterion. In our $Y_p$ determination, we use these five galaxies excluding the rest, i.e., J1631+4426, J0133+1342, J0825+3532, J0125+0759, and J0935-0115.

To check whether our choice of the flux measuring method (Sections 4.1.1) has any impact on the YMCMC analysis, we solve for the best-fit parameters of the Subaru galaxies with the optical fluxes of the integration method using the YMCMC code. Applying the $\chi^2$-squared criterion, we identify six galaxies (J1016+3754 and all galaxies eliminated above), whose physical parameters are not reliably recovered with the line fluxes. We find that these galaxies tend to have larger $\chi^2_{\text{YMCMC}}$ values than those derived with the optical line fluxes by the method of the Gaussian fit, regardless of whether they meet the $\chi^2$-squared criterion or not. As an example, Figure 4 shows histograms for the distributions of the reproduced line flux ratios of J1016+3754, derived at each step of the YMCMC analysis in both cases of the optical fluxes of the Gaussian fitting method and the integration method together with $\chi^2_{\text{YMCMC}}$ values of 3.33 and 25.70, respectively. While the He λ6678 line is reproduced within 1σ in the former case, it is not reproduced accurately (beyond the 3σ level) in the latter case, which may be attributed to the systematics made by the residual offset in the continuum-subtracted spectrum in the window of the integration. However, the derived $y$ values of the Subaru galaxies in both cases of the optical fluxes are consistent, which makes almost no difference to the $Y_p$ determination (see Section 5.1).

### 4.2.3. Neutral He Abundances

The contributions from $y^0$ can be estimated from the hardness of the ionizing radiation with the radiation softness parameter, $\eta_{\text{obs}}$ (Vilchez & Pagel 1988), defined as

$$
\eta_{\text{obs}} = \frac{O^+ S^{++}}{S^+ O^{++}}.
$$

We calculate $O^+$, $O^{++}$, $S^+$, and $S^{++}$ with emission lines [OII] $\lambda\lambda7320$, 7330, [OIII]$\lambda\lambda5007$, [SII]$\lambda\lambda6717$, 6731, and [SIII] $\lambda\lambda9069$ for the Subaru galaxies (Dors et al. 2016). Table 5 lists the $\eta_{\text{obs}}$ values of the Subaru galaxies. All of the Subaru galaxies have $\log \eta_{\text{obs}} \lesssim 0.9$. Because Pagel et al. (1992) find that the abundance of neutral helium is negligible for a galaxy with $\log \eta_{\text{obs}} \lesssim 0.9$, we conclude that $y^0$ is negligible for the Subaru galaxies.

### 4.3. O Abundance

We use the oxygen abundance reported in previous studies, which are measured by the direct method. Table 4 lists the oxygen abundances of the Subaru galaxies and their references.

## 5. Results

### 5.1. Primordial He Abundance

In the framework of the Big Bang cosmology, the helium element is produced by BBN and galactic chemical enrichment, while virtually no oxygen is created in the BBN. Peimbert & Torres-Peimbert (1974, 1976) have proposed to determine $Y_p$ with helium and oxygen abundance measurements by the linear regression of the form

$$
Y = Y_p + \frac{dY}{d(O/H)}(O/H),
$$

\[\text{(5)}\]
where $Y$ is the helium mass fraction of a galaxy. $Y$ is derived with the equations

\begin{align}
Y &= \frac{4y}{1 + 4y}(1 - Z) \quad \text{and} \\
Z &= c \times (O/H),
\end{align}

where $Z$ and $c$ are the heavy-element mass fraction and the coefficient, respectively. Because $c$ is uncertain, the $y$ values cannot be precisely converted to $Y$ values. To avoid the uncertainty, Hsyu et al. (2020) have derived the primordial helium number abundance ratio $y_p$ in the $y - (O/H)$ plane by linear regression of the form

\begin{align}
y = y_p + \frac{dy}{d(O/H)}(O/H).
\end{align}

The likelihood function of their linear model does not contain terms corresponding to the uncertainties of $O/H$ measurements, while Hsyu et al. (2020) change the likelihood function with new values of $O/H$ from Gaussian distributions.
with the means of the observed values and the standard deviations of their errors at each step of MCMC sampling. In our study, to account for the uncertainties of O/H measurements in the same way as y uncertainties, we consider the probability of obtaining the O/H measurements arising from "true" values. We maximize the log-likelihood function given by

$$\log(L) = -\frac{1}{2} \sum_i \left[ \left( y_i - a \frac{O}{H} - b \right)^2 \right. $$

$$\left. \sigma_N^2 + a^2 \sigma_{O/H}^2 + \sigma_{int}^2 \right] $$

$$+ \log(\sigma_N^2 + a^2 \sigma_{O/H}^2 + \sigma_{int}^2),$$

with a slope $a \equiv dy/d(O/H)$ and a primordial helium number abundance ratio $b \equiv y_p$, and an intrinsic dispersion $\sigma_{int}$ that is introduced for capturing unrecognized systematics of measurements (Cooke et al. 2018; Hsyu et al. 2020). Here, $y_i$ ($\sigma_y$) and $O/He$ ($\sigma_{O/H}$) are the measured y values (errors) and O/H values (errors), respectively. The summation of Equation (9) is over all galaxies in the sample. The result for our sample of the 64 galaxies is shown in Figure 5. The regression yields

$$y_p = 0.0777^{+0.0015}_{-0.0014},$$

$$\frac{dy}{d(O/H)} = 75^{+13}_{-14},$$

$$\sigma_{int} \leq 0.0019 \ (95\%).$$

Note that we quote a 2σ upper limit on $\sigma_{int}$ because it is consistent with zero. Converting our $y_p$ value to the mass fraction $Y_p$ via $Y_p = 4y_p/(1 + 4y_p)$, we obtain

$$Y_p = 0.2370^{+0.0034}_{-0.0033}.$$  

We compare the $Y_p$ measurement of our study with those of previous studies in Figure 6. Our $Y_p$ measurement is comparable with those obtained by methods similar to ours (Aver et al. 2015; Peimbert et al. 2016; Fernández et al. 2019; Valerdi et al. 2019; Hsyu et al. 2020; Kurichin et al. 2021). However, our measurement is lower than the previous measurements at the $\sim1\sigma$ level.

To explore the source of the $\sim1\sigma$-level difference, we apply our linear-regression method of Equation (9) to the sample of Hsyu et al. (2020), and present the obtained $Y_p$ value in Figure 6 together with the one derived by Hsyu et al. (2020). Although the linear-regression method of Hsyu et al. (2020) is
different from our method, we confirm that our and Hsyu et al. (2020)’s results are almost identical, albeit with a negligibly small difference produced by the linear-regression methods. We also derive the $Y_p$ value with the line fluxes obtained by the integration method to test whether the difference in the optical-flux-measuring methods affects our result. In this case, for the four Subaru galaxies that meet the qualification criterion (see Section 4.2.2) and the literature galaxies, we obtained $Y_p = 0.2373^{+0.0035}_{-0.0034}$. This value is almost the same as the one obtained from Equation (11). We therefore conclude that our choice of the flux measurement method makes almost no difference to our result.

Because the main difference between our study and that of Hsyu et al. (2020) is the inclusion of the EMPGs, we conclude that the source of the $\sim 1\sigma$-level difference is the EMPGs covering the metal-poor end (i.e., small O/H) that is key for the $Y_p$ determination (Figure 5). Our $Y_p$ value is in agreement with the one inferred from the CMB measurements (Planck Collaboration et al. 2020) as well as the analysis of an absorption system in near-pristine intergalactic gas clouds along the light of a background quasar (Cooke & Fumagalli 2018).

5.2. Constraint on $N_{\text{eff}}$

The $Y_p$ value provides powerful constrains on the cosmological parameters. In the framework of the standard BBN model, $Y_p$ strongly depends both on the baryon-to-photon ratio $\eta$ and the $N_{\text{eff}}$ value. We constrain $\eta$ and $N_{\text{eff}}$ with our $Y_p$ measurement and the primordial deuterium abundance $D_p$ measurement of $D_p = (2.527 \pm 0.030) \times 10^{-5}$ (Cooke et al. 2018) by minimizing

$$
\chi^2(\eta, N_{\text{eff}}) = \frac{(Y_p,\text{obs} - Y_p,\text{mod}(\eta, N_{\text{eff}}))^2}{\sigma_{Y_p,\text{obs}} + \sigma_{Y_p,\text{mod}}} + \frac{(D_p,\text{obs} - D_p,\text{mod}(\eta, N_{\text{eff}}))^2}{\sigma_{D_p,\text{obs}} + \sigma_{D_p,\text{mod}}}
$$

(12)

with respect to $N_{\text{eff}}$ and $\eta$, where the subscripts obs and mod denote the observational values and the theoretical BBN model values, respectively. To calculate the $Y_p,\text{mod}$ and $D_p,\text{mod}$ values for given values of $N_{\text{eff}}$ and $\eta$, we use version 3.0 of the PArthEnoPE BBN code (Gariazzo et al. 2022), fixing all input parameters of PArthEnoPE except $N_{\text{eff}}$ and $\eta$ to the standard values. In the calculation of $D_p,\text{mod}$ and $Y_p,\text{mod}$, we use the neutron lifetime $\tau_n = 879.4 \pm 0.6$ s (Particle Data Group et al. 2020) and the relevant nuclear reaction rates from Pisanti et al. (2021). The errors of the $\tau_n$ and the nuclear reaction rates propagate to the errors of $D_p,\text{mod}$ and $Y_p,\text{mod}$. In Equation (12), $\sigma_{D_p,\text{mod}} = (0.06) \times 10^{-10}$ is the error of $D_p,\text{mod}$ due to the uncertainty of the nuclear reaction rates, and $\sigma_{Y_p,\text{mod}} = (0.0003)^2 + (0.00012)^2$ is the error of $Y_p,\text{mod}$, where the two terms correspond to the uncertainties of the nuclear reaction rates and $\tau_n$, respectively (Gariazzo et al. 2022). We find

$$
N_{\text{eff}} = 2.37^{+0.19}_{-0.24},
$$

$$
\eta \times 10^{10} = 5.80^{+0.13}_{-0.16}.
$$

Figure 7 presents our constraint on $\eta$ and $N_{\text{eff}}$ and comparison with the result of Hsyu et al. (2020). Our constraint is consistent with the one of Hsyu et al. (2020) within the $1\sigma$ error, while our best-estimate values are slightly smaller than those of Hsyu et al. (2020).

6. Discussion

If $N_{\text{eff}}$ becomes smaller, the values of $Y_p$ and $D_p$ decrease. This is because the $\beta$ equilibrium between neutrons and protons continues for longer time reducing the abundance of neutrons, which are processed into light elements during the BBN. On the other hand, the smaller $\eta$ gets, the larger $D_p$ becomes because the reactions that deplete deuterium become inefficient. Therefore, our smaller value of $Y_p$ leads to smaller values of $N_{\text{eff}}$ and $\eta$. Figure 8 presents the constraint on $\eta$ and $N_{\text{eff}}$, together with the one on $\eta$ obtained by Planck Collaboration et al. (2020). Our constraints suggest that there is a potential $\geq 2\sigma$ tension with the Standard Model that predicts $N_{\text{eff}} = 3.046$ (Figure 8). Moreover, our constraints agree with the Planck measurement in $\eta$ only at the $1–2\sigma$ level. This may be a hint of an electron neutrino $\nu_e$ to antielectron neutrino $\bar{\nu}_e$ asymmetry (i.e., lepton asymmetry), because the $\nu_e - \bar{\nu}_e$ asymmetry shifts the beta equilibrium between protons and neutrons before BBN, which changes the primordial element abundances. If $\nu_e$ increases (decrease), the primordial element abundances decrease (increase). The $\nu_e - \bar{\nu}_e$ asymmetry is represented by the degeneracy parameter of the electron neutrino, $\xi_e = \mu_{\nu_e}/T_{\nu_e}$.
in natural units, where $\mu_{\nu_e}$ and $T_{\nu_e}$ are the chemical potential and the temperature of $\nu_e$, respectively. Here $\xi_e$ can be both negative and positive, and the $\nu_e - \bar{\nu}_e$ asymmetry is given by

$$n_{\nu_e} - n_{\bar{\nu}_e} \propto (\sigma^2 + \xi^2)T_{\nu_e}^3$$

with the Fermi–Dirac distribution function, where $n_{\nu_e}$ ($n_{\bar{\nu}_e}$) is the number density of (anti)electron neutrinos. Although the standard cosmology assumes $\xi_e = 0$, so far whether this assumption is true is not revealed by the Standard Model nor astronomical observations (e.g., Kohri et al. 1997; Popa & Vasile 2008; Caramete & Popa 2014; Oldengott & Schwarz 2017; Nunes & Bonilla 2017). Our low $Y_p$ value (Figure 6) may imply $\xi_e > 0$ (Kohri et al. 1997; Sato et al. 1998), while there are other possibilities (e.g., Kohri & Maeda 2022).

To constrain $\xi_e$ as well as $N_{\text{eff}}$ and $\eta$, we minimize

$$\chi^2(\eta, N_{\text{eff}}, \xi_e) = \frac{(Y_{p, \text{obs}} - Y_{p, \text{mod}}(\eta, N_{\text{eff}}, \xi_e))^2}{\sigma^2_{Y_p, \text{obs}} + \sigma^2_{Y_p, \text{mod}}}$$

$$+ \frac{(D_{p, \text{obs}} - D_{p, \text{mod}}(\eta, N_{\text{eff}}, \xi_e))^2}{\sigma^2_{D_p, \text{obs}} + \sigma^2_{D_p, \text{mod}}} + \frac{(\eta - 6.132)^2}{0.038^2},$$

allowing $\xi_e$, $N_{\text{eff}}$, and $\eta$ to vary independently of each other as input parameters of PArthEnOPE. In Equation (15), in order to break the degeneracy between the parameters, we impose a Gaussian prior of $\eta \times 10^{10} = 6.132 \pm 0.038$, which comes from the marginalized constraint on the baryon density by Planck Collaboration et al. (2020), where $N_{\text{eff}}$ and $Y_p$ are treated as free parameters. Figure 9 presents two-dimensional marginalized constraints on the three parameters of $\xi_e$, $N_{\text{eff}}$, and $\eta$. The gray contours show the constraint obtained without the prior of $\eta$, illustrating a degeneracy between the three parameters. The vertical dotted lines correspond to the Planck measurement of $\eta$. In the left two panels of Figure 9, the gray and dotted contours intersect in a region of the parameter spaces. With the full combined results from the $Y_p$, $D_p$, and $\eta$ measurements, we break the parameter degeneracy, and find

$$N_{\text{eff}} = 3.11^{+0.34}_{-0.31},$$

(16)

$$\eta \times 10^{10} = 6.08^{+0.06}_{-0.06},$$

(17)

$$\xi_e = 0.05^{+0.03}_{-0.02}.$$  

(18)

The derived $\xi_e$ value is higher than zero at the $\sim 2\sigma$ level. This may be a hint of a lepton asymmetry with an excess in the number of $\nu_e$ compared to that of $\bar{\nu}_e$. To realize the universe with $\xi_e \sim 0.05$, new physics for lepton number generation may be required (Kawasaki & Murai 2022).

As shown in the right panel of Figure 9, there is a correlation between $\xi_e$ and $N_{\text{eff}}$. This is because the effects of $N_{\text{eff}}$ and $\xi_e$ on the BBN compensate for each other. A positive value of $\xi_e$ decreases the number of neutrons, which are in equilibrium with protons, while a $N_{\text{eff}}$ value larger than 3.046 ends the equilibrium at an earlier time, which means more neutrons are left before the BBN. Our positive value of $\xi_e$ allows for values of $N_{\text{eff}}$ significantly higher than the results obtained from
Equation (13). While the \( N_{\text{eff}} \) value of our best estimate (Equation (16)) is comparable with the one of the Standard Model (\( N_{\text{eff}} = 3.046 \)), our best estimate could be as high as \( N_{\text{eff}} = 3.45 \), which can ameliorate the Hubble tension (Section 1), at the 68% confidence level. Using the results of previous studies using a method similar to ours (Aver et al. 2015; Peimbert et al. 2016; Fernández et al. 2019; Valerdi et al. 2019; Hsyu et al. 2020; Kurichin et al. 2021), we also confirm this trend of the central values of \( \xi > 0 \) and \( N_{\text{eff}} > 3.046 \) allowing for \( N_{\text{eff}} \approx 3.4 \) at the 68% confidence level. This trend is consistent with the cosmological model proposed by Seto & Toda (2021) to reduce the Hubble tension without spoiling BBN. Because the contribution of \( \xi < 0.05 \) toward increasing the \( N_{\text{eff}} \) value from 3.046 is small \( (\lesssim 0.01) \) with the Fermi–Dirac distribution function, the existence of extra radiation is necessary to realize \( N_{\text{eff}} \approx 3.4 \). Although the errors of our measurements are still too large to conclude, there is a possibility of the \( \nu_e - \bar{\nu_e} \) asymmetry and extra radiation, which may provide the high \( N_{\text{eff}} \) value that resolves the Hubble tension (Section 1).

7. Summary

Using Subaru/MOIRCS, IRCs, and SWIMS, we conducted NIR spectroscopic observations covering the He \( \lambda \lambda 10830 \) line for galaxies that are classified as EMPGs with a metallicity lower than 0.1 solar metallicity. Removing one EMPG with a clear signature of outflows, we determine the He abundances of the 10 (= 11 – 1) galaxies using the NIR spectroscopic data and the pre-existing optical spectroscopic data. We explore the best-fit physical parameters of the nebulae with the observed line fluxes by the MCMC technique. Selecting the 5 EMPGs from the Subaru galaxies whose physical properties are reliably determined, we construct a sample of a total of 59 galaxies consisting of our 5 EMPGs and 54 galaxies (including 3 EMPGs) taken from the literature, increasing the number of EMPGs that are key for primordial He abundance \( Y_p \) determination from 3 to 8 (=3+5). We derive \( Y_p \) using these 59 galaxies and constrain the effective number of the neutrino species \( N_{\text{eff}} \), the baryon-to-photon ratio \( \eta \), and the electron-neutrino degeneracy parameter \( \xi_e \). Our main results are summarized below.

1. The linear regression \( y = (O/H) \) for the 59 galaxies gives \( Y_p = 0.2370_{-0.0033}^{+0.0034} \). Our \( Y_p \) value is in agreement with the one inferred from the CMB measurements (Planck Collaboration et al. 2020), and comparable with those of the previous galaxy observations.

2. With our \( Y_p \) value and the \( D_L \) measurement given by Cooke et al. (2018), we obtain \( N_{\text{eff}} = 2.37_{-0.24}^{+0.19} \) and \( \eta \times 10^{10} = 5.80_{-0.16}^{+0.13} \) by \( \chi^2 \) minimization. The constraint on \( N_{\text{eff}} \) is in a potential \( >2\sigma \) tension with the Standard Model predicting \( N_{\text{eff}} = 3.046 \).

3. Motivated by the potential tension, we allow a \( \nu_e - \bar{\nu_e} \) asymmetry (i.e., nonzero \( \xi_e \)) for the \( N_{\text{eff}} \) and \( \eta \) constraints. We obtain the best-fit parameters, \( \xi_e = 0.05_{-0.02}^{+0.03} \), \( N_{\text{eff}} = 3.11_{-0.34}^{+0.31} \), and \( \eta \times 10^{10} = 6.08_{-0.06}^{+0.04} \), where the \( N_{\text{eff}} \) and \( \eta \) values agree with the Standard Model and the Planck measurement, respectively. Our constraints suggest a \( \nu_e - \bar{\nu_e} \) asymmetry and allow for a high value of \( N_{\text{eff}} \) up to \( N_{\text{eff}} = 3.45 \) within the 1\( \sigma \) level, which may mitigate the Hubble tension.

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Software: corner.py (Foreman-Mackey 2016), emcee (Foreman-Mackey et al. 2013), Matplotlib (Hunter 2007), SciPy (Virtanen et al. 2020).

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