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Subaru/FOCAS IFU revealed the metallicity gradient of a local extremely metal-poor galaxy

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Abstract

We present the first measurement of the metallicity gradient in extremely metal-poor galaxies (EMPGs). With Subaru/Faint Object Camera And Spectrograph (FOCAS) Integral Field Unit (IFU), we have observed a nearby, low-mass EMPG, HSC J1631+4426, whose oxygen abundance and stellar mass are known to be $12 + \log (O/H) = 6.9$ and $\log_{10}(M_\star/M_\odot) = 5.8$, respectively. The measured metallicity gradient is $-0.36 \pm 0.04$ dex kpc$^{-1}$ corresponding to $-0.049 \pm 0.006$ dex $R_{\text{e}}^{-1}$ for the continuum effective radius of $R_{\text{e}} = 0.14$ kpc. Our observation has successfully demonstrated that three-dimensional spectroscopy with 8m-class telescopes is powerful enough to reveal the metallicity distribution in local EMPGs, providing precious information on the baryon cycle in local analogs of primordial galaxies in the early Universe.

Key words: galaxies: abundances — galaxies: dwarf — galaxies: evolution — galaxies: individual (HSC J1631+4426) — galaxies: ISM

1 Introduction

The metallicity of galaxies is the key to unveiling their formation and evolution processes (e.g., Pagel 1997). The metallicity gradient, expressed in dex kpc$^{-1}$ or dex $R_{\text{e}}^{-1}$, where $R_{\text{e}}$ is the effective radius, is one of the important diagnostics for evaluating gaseous flows in the interstellar medium (ISM) and its mixing processes (e.g., Sharda et al. 2021). Observations have demonstrated that normal disk
galaxies in the local Universe and dwarf galaxies in Local Group have negative metallicity gradients (e.g., Belfiore et al. 2017 and references therein). In the “inside-out” galaxy growth scenario in which the star formation begins at the central part of the galaxy and propagates to the outer region, the metallicity gradient is negative and steep in the early stage and flattens as the galaxy grows in size and mass (Wang et al. 2019 and references therein). On the other hand, there are also several galaxies that have positive metallicity gradients in both the local and distant Universe (e.g., Wang et al. 2019; Belfiore et al. 2017; Cresci et al. 2010). The positive gradient observed in high-z galaxies indicates the gas accretion to their central part in the “cold mode,” with the accretion of pristine gas from the cosmic web (Sánchez Almeida et al. 2013). Since these studies commonly target galaxies with $12 + \log(O/H) \geq 8$, metallicity gradients in metal-poor galaxies are observationally hitherto unknown.

In this paper, we report a negative metallicity gradient in a local extremely metal-poor galaxy (EMPG), HSC J1631+4426, whose metallicity falls within this unexplored range. EMPGs are defined as galaxies with an oxygen abundance lower than $12 + \log(O/H) = 7.69$, which is equivalent to 10% solar metallicity (Sánchez Almeida et al. 2013; Kojima et al. 2020; Isobe et al. 2021). They are believed to be the dominant population in the early Universe. Local EMPGs are of great importance as analogs of high-z galaxies which are difficult to observe directly. More than 90% of EMPGs have diffuse structures in their immediate vicinity (Isobe et al. 2021). Preceding studies suggest that EMPGs are star-forming regions in such diffuse host galaxies whose metallicities are higher than the metal-poor parts, indicating positive metallicity gradients when considered their whole structure (Sánchez Almeida et al. 2013, 2016; Olmo-García et al. 2017). Our result suggests a possible diversity of metallicity gradients in EMPGs.

The rest of this paper is organized as follows. In section 2, observational information and the data reduction process are presented. In section 3, we explain the method of flux measurement and gas-phase oxygen abundance (i.e., metallicity) calculation. Section 4 describes the measurement of the metallicity gradient and discusses its relation with the central metallicity and stellar mass. Throughout this paper, a standard ΛCDM cosmology with parameters of $(\Omega_m, \Omega_{\Lambda}, H_0) = (0.286, 0.714, 69.6$ km s$^{-1}$ Mpc$^{-1}$) is adopted. This cosmology gives a scale of $0.629\text{kip arcsec}^{-1}$ at $z = 0.03125$. Solar metallicity $Z_\odot$ is defined by $12 + \log(O/H) = 8.69$ (Asplund et al. 2009).

2 Observation and data reduction

Our target, HSC J1631+4426, is identified to be the most metal-poor galaxy with a 1.6% solar metallicity [i.e., $12 + \log(O/H) = 6.90$; Kojima et al. 2020]. HSC J1631+4426 is a local dwarf galaxy at redshift $z = 0.03125$, which was discovered in a metal-poor galaxy survey program named the Extremely Metal-Poor Representatives Explored by the Subaru Survey (EMPRESS; Kojima et al. 2020). Its stellar mass is log$(M_*/M_\odot) = 5.8$ and its effective radius is measured as $R_e = 137\pm 9$ pc using the Subaru Hyper Supreme-Cam (HSC) $i$-band surface brightness profile (Isobe et al. 2021). To reveal the metallicity distribution of the galaxy, we utilize the Faint Object Camera And Spectrograph (FOCAS; Kashikawa et al. 2002) Integral Field Unit (IFU: Ozaki et al. 2020) mounted on the Subaru telescope. We carried out integral field spectroscopy for the target galaxy, HSC J1631+4426 (RA = 16h31m14s, Dec = +44°26′04′′.43), on 2020 March 6 with FOCAS IFU (PI: S. Fujimoto). We obtained a single 1200 s exposure using the 300B grism and the SY47 filter with the wavelength coverage of 4700–7600 Å and the spectral resolution of $R = \lambda/\Delta \lambda \sim 900$. An O-type subdwarf, HZ44 (RA = 13°23′35″.263, Dec = +36°07′59″.55) was also observed as a standard star. During the observation, the atmospheric condition was good with the seeing size varying between 0.6 and 0.7.

To reduce the target and the standard star data, we used the FOCAS IFU pipeline software. A detailed explanation of the reduction flow is given in Ozaki et al. (2020). The size of spatial pixel (called spaxel) and spectral pixel of the final data cube are $0.′′435 \times 0.′′211$ and 1.34 Å, respectively. The total field of view is $10′.0 \times 13′.5$.

3 Analysis

We visually identified four emission lines (Hα, Hβ, [O III]4959, and [O III]5007) in our data cube. The velocity full widths at half-maximum (FWHMs) of the lines are $\sim 300$ km s$^{-1}$ (i.e., 5–6 spectral pixels). They are approximately equal to the velocity resolution: the lines are unresolved. We integrated the data cube over twice the FWHM for each line to create the velocity-integrated line intensity map. For each velocity-integration, we subtracted continuum (or sky-residual in spaxels without the object). The continuum (or sky-residual) level in each spaxel was obtained by integrating the spectra in the wavelength around the emission line over the same number of spectral pixels as that in the line map. The wavelength range was carefully chosen in order not to include any emission lines. Figure 1 shows the results.

1 For the sake of simplicity, we refer hereafter to gas-phase oxygen abundance (i.e., not in the stellar atmosphere) as metallicity.

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As shown in the figure 1a Hα map, we defined four regions: the Entire region, the EMPG region, the Tail-1 region, and the Tail-2 region. The latter two regions correspond to the diffuse structures found in the continuum image (Isobe et al. 2021). We measured the total line fluxes for each region by summing up the intensity within the region of each line intensity map. As flux errors, we used rms per spaxel calculated from the spaxels outside of the Entire region and scaled it by the square-root of the number of the spatial pixels. We also measured the upper limits of the line fluxes of [NII]6584, [SII]6717, and [SII]6731. We corrected the total fluxes for the dust extinction within the Milky Way by utilizing the Galactic Dust Reddening and Extinction Service provided by NASA/IPAC Infrared Science Archive (IRSA) and the Cardelli, Clayton, and Mathis (1989) extinction curve. Visual extinction by the Milky Way toward the target galaxy is $A_{MW}(V) = 0.0237$ mag. The corrected line fluxes and upper limits are listed in Table 1.

For the dust attenuation in the target galaxy, we estimated the color excess $E(B-V)$ for each region based on the Hα/Hβ line ratio, the Balmer Decrement, under the assumptions of the Cardelli, Clayton, and Mathis (1989) extinction curve, the electron temperature $T_e = 25000$ K measured by [O III]4363 (Kojima et al. 2020), and the case B approximation (Osterbrock 1989). The obtained $E(B-V)$ values are listed in Table 1. Since we obtained non-zero $E(B-V)$ only for the Tail-1 region, we applied the internal dust attenuation correction only for that region, assuming the Cardelli, Clayton, and Mathis (1989) extinction curve.

The gas-phase metallicity, $12 + \log(O/H)$, for each region was estimated from the $R_3$ index: $R_3 \equiv [O III]5007/H\beta$ (Maiolino & Mannucci 2019). Since
the relation between $R_3$ and $12 + \log(O/H)$ is known to be a binary function, there can be high and low $12 + \log(O/H)$ branches for a value of $R_3$. To know the more likely case, we also examined the $N_2$ index: $N_2(=\text{[N II]}6584/\text{H}\alpha)$. Although the [N II]6584 line is not detected in the galaxy, its upper limit can be useful to reject the high $12 + \log(O/H)$ solution.

First, we calculated the $R_3$ and $N_2$ indices for each region, using the dust-corrected total line fluxes and upper limits. Next, we used the empirical relation by Curti et al. (2020) calibrated for the $N_2$ index to obtain upper limits of $12 + \log(O/H)$. We found that all regions should have $12 + \log(O/H) < 7.728-8.550$, which is consistent with the EMPG nature (Kojima et al. 2020). Curti et al. (2020) also present the $R_3$ calibration, which is limited to $12 + \log(O/H) > 7.6$, while the target galaxy is an EMPG (Kojima et al. 2020). We then used the theoretical models by Inoue (2011) which cover a very wide range of $12 + \log(O/H)$. The models were calculated by CLOUDY (Ferland et al. 1998) for the cases with gas-phase metallicity $[\log(Z/Z_\odot)] = -\infty, -5.3, -3.3, -1.7, -0.7, -0.4,$ and 0.0, ionization parameter $(-3 \leq \log_{10}U \leq -1)$, and hydrogen number density ($0 \leq \log_{10}(n_H/cm^3) \leq 2$). They also changed the input stellar spectra depending on the metallicity (gas and stellar metallicities were assumed to be the same). Finally, they presented the emission line intensities normalized by H$\beta$ as a function of metallicity, averaging over the 25 different sets of $(U, n_H)$ in each metallicity case. They noted that the standard deviations of the line ratios relative to H$\beta$ are 5%–25%. The obtained average line ratios are consistent with observations as shown in their figure 1 for some strong emission lines, including [O III] lines. Since the metallicity grid of the line ratios was sparse, we used the following interpolation function:

$$\log_{10}(R_3) = \begin{cases} 9.4272 \times 10^{-1} x - 6.5028 & \text{for } x \leq 6.9910, \\ -5.2795 \times 10^{-4} x^4 + 3.7631 \times 10^{-1} x^3 + 3.2170 \times 10^{-2} x^2 - 1.8000 x + 3.2803 & \text{for } x > 6.9910, \end{cases}$$

(1)

where $x = 12 + \log(O/H)$. The obtained $12 + \log(O/H)$ for each region are summarized in Table 1.

Figure 2 shows our $12 + \log(O/H)$ for each region with error bars, plotted along with those reported by Kojima et al. (2020). We added systematic uncertainty of $\pm0.1$ to the results based on empirical calibrations because such dispersion exists in these calibrations (e.g., Maiolino & Mannucci 2019). The oxygen abundances for the Entire, EMPG, and Tail-1 regions are consistent with each other within the uncertainty when the systematic errors are considered. The oxygen abundance of the Tail-2 region may be lower than the other three regions, although the uncertainty is large.

There is a systematic offset of our $12 + \log(O/H)$ values from that obtained by a direct temperature method in Kojima et al. (2020). We could not detect the [O III]4363 in our data cube because of the short exposure. It is a future work to apply the direct temperature method to the target galaxy in a spatially resolved way after taking a deeper data set (see also the discussion below).

### Table 1. Measurement of emission lines, color excess, and metallicity for the four regions.*

| Region     | $H\beta$ | [O III]4959 | [O III]5007 | H$\alpha$ | [N II]6584 | [S II]6717 | [S II]6731 | $E(B-V)$ | $12 + \log(O/H)$ |
|------------|----------|-------------|-------------|-----------|------------|-----------|-----------|----------|-----------------|
| Entire     | 953.5 ± 16.7 | 396.6 ± 15.1 | 1467.1 ± 13.9 | 2493.7 ± 11.1 | <31.6 | <189.0 | <1484.9 | <0.0503 | 7.101 ± 0.010 |
| EMPG       | 867.6 ± 11.2 | 427.5 ± 10.0 | 1408.6 ± 9.3 | 2367.6 ± 7.4 | <21.1 | <126.0 | <990.0 | <0.0338 | 7.128 ± 0.007 |
| Tail-1     | 15.0 ± 3.9  | <10.4       | 21.4 ± 3.3  | 57.7 ± 2.6  | <7.4  | <44.6  | <350.0  | 0.349 ± 0.114 | 7.043 ± 0.133 |
| Tail-2     | 27.0 ± 6.4  | <17.2       | 20.8 ± 5.3  | 65.7 ± 4.3  | <12.0 | <72.1  | <567.1  | <0.789  | 6.778 ± 0.138 |

*Measurement for the total fluxes after the correction for the Milky Way dust attenuation, $E(B-V)$ in the target galaxy, and $12 + \log(O/H)$. The observed total flux within each region is given in units of $10^{-18}$ erg cm$^{-2}$ s$^{-1}$. Upper limits are given at the 3σ level.
4 Metallicity gradient measurement

To derive the metallicity gradient, we created a metallicity map by calculating $12 + \log (O/H)$ for each spaxel based on the $R_1$ index as in section 3. Since the H$\beta$ line flux is required in the denominator of the $R_1$ index, we restricted ourselves to the spaxels where the S/N of H$\beta$ is larger than 3, which are confined only in the EMPG region. The line fluxes corrected only for the Milky Way dust extinction were used for the calculation because $E(B-V)$ in the EMPG region is consistent with zero (table 1). In this paper, we present the metallicity gradient purely observationally and do not consider any geometric model to correct for the inclination effect. Since our target galaxy is not edge-on, the projection effect on the distance may not be too large. We assumed the center of the galaxy to be the intensity peak position of the H$\alpha$ map and calculated the projected distance of each spaxel from the center. Note that the kinematic center of the H$\alpha$ emission is consistent with its intensity peak (Y. Isobe et al. in preparation).

Figure 3 shows the obtained radial profile of the metallicity in the EMPG region. It is important to consider the beam smearing effect on metallicity gradient measurements (Yuan et al. 2013). Since our metallicity measurements reach a scale two times larger than the seeing size ($\approx 0.7 = 0.44 \text{kpc}$), the beam smearing effect would not be large. We fitted the binned data and their standard deviations with a linear function by a $\chi^2$ method, varying both the central metallicity and the gradient. We obtained $-0.36 \pm 0.04 \text{dex kpc}^{-1}$ as the metallicity gradient as well as a central metallicity of $12 + \log (O/H) = 7.276 \pm 0.001$. Note that the observational seeing of 0.7 does not affect the linear function fit because a linear function is conserved by a Gaussian convolution. We also obtained a consistent gradient value even when we divided the data into two groups (i.e., the inside and the outside of 0.44 kpc).

To evaluate the properties of our galaxy, we compare our result with previous studies. Figure 4 shows the metallicity gradient as functions of the central metallicity (a) and the stellar mass (b), respectively. Our work successfully reports the metallicity gradient in a considerably metal-poor, low-mass galaxy with $(M_*/M_\odot) \sim 6$ for the first time. The metallicity gradient of our EMPG in units of dex kpc$^{-1}$ is considerably steep compared to those observed in local high-mass galaxies, which are almost flat $[\log (M_*/M_\odot) \sim 9]$. This steep gradient can be interpreted by a simple chemical evolution model as follows.

A simple closed-box model approximately gives the time evolution of oxygen abundance as $Z_o \approx \gamma_o (t/\tau_{SF})$ when $t < \tau_{SF}$ (Pagel 1997), where $\gamma_o$ is the stellar yield of oxygen and $\tau_{SF}$ is the time-scale of star formation. This equation can be reduced to

$$\frac{\Delta \log (O/H)}{\tau_{SF}} = \ln 10 \left( \frac{Z_o}{\gamma_o} \right) \frac{\Delta 12 + \log (O/H)}{\Delta R} \Delta R \approx 0.02 \left( \frac{\Delta R}{1 \text{kpc}} \right),$$

(2)

when we adopt $Z_o \approx 0.02 Z_\odot$ (Kojima et al. 2020), $Z_\odot = 5.7 \times 10^{-3}$ (Asplund et al. 2009), $\gamma_o = 0.004$ (Meynet & Maeder 2002; Sánchez Almeida et al. 2015), and our metallicity gradient of $||\Delta 12 + \log (O/H)||/\Delta R || = 0.36 \text{kpc}^{-1}$. Therefore, the observed metallicity gradient can be realized quickly compared to the galaxy evolution (i.e., $\tau_{SF}$). On the other hand, the ISM mixing time-scale is $\tau_{mix}$ with the mixing velocity $v_{mix}$. The presented data cube of the H$\alpha$ line indicates a velocity gradient of $\sim 30 \text{km s}^{-1}$. Assuming $v_{mix}$ to be the same order of that velocity, we find

$$\frac{\Delta \log (O/H)}{\tau_{mix}} = 0.7 \left( \frac{\tau_{mix}}{1 \text{Gyr}} \right) \left( \frac{v_{mix}}{30 \text{ km s}^{-1}} \right),$$

(3)

If $\tau_{SF} \lesssim 1 \text{ Gyr}$, a metallicity gradient produced by the chemical enrichment can be kept against the ISM mixing. The observed steep negative gradient indicates inside-out star formation in the EMPG and its inefficient ISM mixing due to a slow turbulent velocity induced by a shallow gravitational potential.

On the origin of the metal-poor gas of EMPGs, Sánchez Almeida et al. (2015) suggest that the cold, metal-poor gas infall from the cosmic web dilutes the metallicity of the central part and triggers star formation there. They also report that diffuse structures have $\sim 1$ dex higher metallicity than...
caused by missing information of the O index method we used may suffer from larger uncertainties that the electron temperature is as high as by the [OII]3727 lines. A potentially more serious case is
clicity (figure 2) only in the central part because the same
distance. This case may lead to a
central part of the EMPG and decreases along the radial
shorter wavelength coverage for [OII]3727 or much deeper
temperature. As a result, the gradient would become shallower
index gives a lower 12
itive metallicity gradients are also observed in some local
consider the whole system including the diffuse structures. Pos-
itive metallicity gradients are also observed in some local and high-z galaxies (Cresci et al. 2010; Sánchez-Menguiano et al. 2016; Wang et al. 2019). On the other hand, the metal-
icities of the two Tail regions in our galaxy are similar to or
lower than the mean of the EMPG region (figure 2) and are
likely to be lower than the central metallicity of the EMPG
region. Although the distances of these regions from the
EMPG center are about ∼2 kpc, outside the range of the
current analysis shown in figure 3, the galaxy we discuss
here probably does not have any positive gradient even if we
include the Tail regions.

A caveat of the analysis in this paper is the possible radial dependence of the nebular parameters. We have implicitly assumed radial constancy of nebular parameters by using the empirical calibration formula. For example, if the ionization parameter changes radially, the empirical R3-index method we used may suffer from larger uncertainties caused by missing information of the O⁺ amount traced by the [OII]3727 lines. A potentially more serious case is that the electron temperature is as high as $T_e = 25000 K$, obtained from [OII]4363 (Kojima et al. 2020), only in the central part of the EMPG and decreases along the radial distance. This case may lead to a ∼0.2 dex lower metallicity (figure 2) only in the central part because the same R3 index gives a lower $12 + \log (O/H)$ value for higher temperature. As a result, the gradient would become shallower than that derived here. Examining these points requires a shorter wavelength coverage for [OII]3727 or much deeper data cube for faint [OIII]4363, which is left for a future work.

Another caveat is the contribution of diffuse ionized gas (DIG) to the emission lines (Zhang et al. 2017; Sanders et al. 2017, 2021). The half-light radius of Hα emission is measured at $R_{\text{Hα}} = 0.61' = 380$ pc from the line map, which is about three times larger than $R_e = 140$ pc of the stellar component measured in the HSC $i$-band image (Isobe et al. 2021). In the GALEX/NUV image, the galaxy is detected but not resolved, providing no spatial information of the young stellar component. If we assume the $i$-band size to be the size of the young stellar component, it is significantly smaller than the spatial extent of the Hα emission. A part of Hα emission may come from DIG. Indeed, the DIG fraction is estimated at ∼0.5 based on equation (24) in Sanders et al. (2017) from the mean Hα surface brightness of $\Sigma_{H\alpha} = L_{H\alpha} / 2\pi R^2_{\text{H\alpha}} = 6 \times 10^{39}$ erg s$^{-1}$ kpc$^{-2}$ in our line map. On the other hand, the metallicity estimated by the R3 index, which we adopted here, may not be affected by the DIG contribution because the R3 indices of HII regions and DIG are similar (Zhang et al. 2017; Sanders et al. 2017). In addition, the DIG correction for the strong line methods for metallicity tends to be small at lower metallicity (Sanders et al. 2021), suggesting the DIG effect on our measurements would be small.

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