Red Supergiant Stars in IC 1613 and Metallicity-dependent Mixing Length in the Evolutionary Model

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Abstract

We report a spectroscopic study on red supergiant stars (RSGs) in the irregular dwarf galaxy IC 1613 in the Local Group. We derive the effective temperatures \(T_{\text{eff}}\) and metallicities of 14 RSGs by synthetic spectral fitting to the spectra observed with the MMIRS instrument on the MMT telescope for a wavelength range from 1.16 to 1.23 \(\mu\)m. A weak bimodal distribution of the RSG metallicity centered on \([\text{Fe/H}] = -0.65\) is found, which is slightly lower than or comparable to that of the Small Magellanic Cloud (SMC). There is no evidence for spatial segregation between the metal-rich \((|\text{Fe/H}| > -0.65)\) and -poor \((|\text{Fe/H}| < -0.65)\) RSGs throughout the galaxy. The mean effective temperature of our RSG sample in IC 1613 is higher by about 250 K than that of the SMC. However, no correlation between \(T_{\text{eff}}\) and metallicity within our RSG sample is found. We calibrate the convective mixing length \(\alpha_{\text{MLT}}\) by comparing stellar evolutionary tracks with the RSG positions on the H-R diagram, finding that models with \(\alpha_{\text{MLT}} = 2.2-2.4H_P\) can best reproduce the effective temperatures of the RSGs in IC 1613 for both Schwarzschild and Ledoux convection criteria. This result supports our previous finding that a metallicity-dependent mixing length is needed to explain the RSG temperatures observed in the Local Group, but we find that this dependence becomes relatively weak for RSGs having a metallicity equal to or less than the SMC metallicity.

Unified Astronomy Thesaurus concepts: Red supergiant stars (1375); Late-type supergiant stars (910); Dwarf irregular galaxies (417)

1. Introduction

Red supergiants (RSGs) are massive stars with initial masses between about 9 and 30 \(M_{\odot}\) at the post-main sequence evolutionary phase, of which the hydrogen envelopes are extended to several hundred solar radii (e.g., Levesque et al. 2005; Ekström et al. 2012). It is important to understand their physical properties such as the effective temperature, radius, and mass-loss rate in order to understand the evolutionary history of RSGs and the exact nature of Type II supernova progenitors.

The effective temperatures of RSGs are determined by the Hayashi limit (Hayashi 1961). Stellar evolutionary models predict that this limit depends mainly on two factors for a given initial mass. One is metallicity, which greatly influences stellar opacity, and the other is the so-called mixing length, which characterizes the efficiency of energy transport by convection in the convective hydrogen envelope (e.g., Elias et al. 1985; Ekström et al. 2012; Chun et al. 2018). The Hayashi limit shifts to a higher temperature for a lower metallicity and a larger mixing length (hereafter, the mixing length is denoted by \(\alpha_{\text{MLT}}\), which is given in units of the local pressure scale height \(H_P\)). The mixing length is a free parameter and needs an empirical calibration. Most stellar evolutionary models adopt a fixed mixing length of \(\alpha_{\text{MLT}} = 2.0\) following the calibration result with the Sun. However, some studies provide evidence that a fixed mixing length is not suitable for all types of stars (e.g., Guenther & Demarque 2000; Bonaca et al. 2012; Tayar et al. 2017) and that the mixing length depends on metallicity for both low- and high-mass stars (Joyce & Chaboyer 2018; Chun et al. 2018). More recently, González-Torá et al. (2021) also found that the standard solar mixing length is not applicable to RSGs in their comparison of effective temperature of the Wolf–Lundmark–Mellotte (WLM) galaxy with the Geneva evolutionary models.

Chun et al. (2018) calibrated the mixing length values in RSGs for various metallicities by comparing a grid of massive star evolutionary models with RSGs observed in the nearby universe, and found that the mixing length decreases for decreasing metallicity. Such a calibration of the mixing length is also important for theoretical predictions of the structure (in particular, the radius) of Type II supernova progenitors as discussed by Chun et al. (2018).

The effective temperatures of RSGs can be inferred from their spectra (Levesque et al. 2005; Davies et al. 2013; Tabernero et al. 2018). However, spectroscopic studies on RSGs in external galaxies are largely limited to the Magellanic Clouds (Levesque et al. 2006), M31 (Massey et al. 2009; Gordon et al. 2016), and M33 (Drout et al. 2012; Gordon et al. 2016). Only a small number of RSGs (about 10) in irregular galaxies with lower-metallicity environments than the LMC metallicity have been investigated in several studies (Levesque & Masse 2012; Britavskiy et al. 2014, 2015; Patrick et al. 2015; Garcia 2018). Therefore, a spectroscopic investigation of a larger sample of RSGs in extragalactic galaxies with a wide range of metallicity from \([\text{Fe/H}] = -0.49\) (e.g., SMC) to \([\text{Fe/H}] = -1.0\) (e.g., Sextans A and Sagittarius Dwarf Irregular galax) would provide important information to constrain stellar evolutionary models of RSGs.

The photometric identification of RSGs for extragalactic galaxies (e.g., NGC 4449, NGC 5055, and NGC 5457 by Chun et al. 2017) including the dwarf irregular galaxy (dIrr) IC 1613 (Chun et al. 2015) has been conducted. IC 1613 is an excellent laboratory in which to study RSGs for a number of reasons. IC 1613 is a gas-rich, isolated galaxy with no past interaction with other galaxies. The distance of about
730 kpc (Dolphin et al. 2001; Pietrzyński et al. 2006), a low inclination of \(i = 38^\circ\) (Lake & Skillman 1989), and the high Galactic latitude implying a low extinction value of \(E(B-V) = 0.02-0.04\) (Sandage 1971; Freedman 1988a; Cole et al. 1999) provide a great opportunity to access the resolved stellar populations with a reasonable exposure time from a ground-based telescope. Several studies indicate that IC 1613 has a nearly constant star formation rate over its entire lifetime (Cole et al. 1999; Skillman et al. 2003, 2014) and hosts old (>10 Gyr), intermediate-age (1–10 Gyr), and young (<1 Gyr) stellar populations. However, most studies of the stellar populations in this galaxy have been focused on the old and intermediate-age stars having metallicity of \([Fe/H] = -1.75\) to \(-1.15\) (Cole et al. 1999; Tikhonov & Galazutdinova 2002; Skillman et al. 2003, 2014; Bernard et al. 2007; Weisz et al. 2014; Chun et al. 2015; Shibbons et al. 2015; Puchta et al. 2019). Studies of the H II regions in this galaxy also indicate a low metallicity of \(12 + \log(O/H) \approx 7.70\) (Kingsburgh & Barlow 1995; Lee et al. 2003). Thus, IC 1613 is known to be an extremely low-metallicity galaxy, being more metal-poor than the SMC (Talent 1980; Davidson & Kinman 1982; Dodorico & Dopita 1983; Peimbert et al. 1988; Herrero et al. 2010).

On the other hand, some studies on young stellar populations in IC 1613 imply different metallicity values. Studies on 3–9 O- and B-type supergiant stars in this galaxy give a metallicity of \([Z] = -0.82\) to \(-0.69\) (Bresolin et al. 2007; Garcia et al. 2014; Bouret et al. 2015). More recently, Berger et al. (2018) found \([Z] = -0.69 \pm 0.24\) with bimodal peaks at \([Z] = -0.50\) and \([Z] = -0.85\) for early B-type blue supergiants. Tautvaišienė et al. (2007) investigated the spectra of three M-type RSGs and found that the average metallicity is \([Fe/H] = -0.67 \pm 0.09\). Britavskiy et al. (2019) investigated six RSGs including the RSG sample of Tautvaišienė et al. (2007). They adopted \([Fe/H] = -0.7\) for IC 1613 and found higher effective temperatures of RSGs than those of the SMC.

In this study, we investigate 14 RSG stars in IC 1613 using low-resolution J-band spectra obtained with the MMT and Magellan infrared spectrograph (MMIRS) on the 6.5 m MMT telescope. We aim to estimate the effective temperatures and metallicities of these RSGs, and calibrate the mixing length in stellar evolutionary models with our RSG sample. In Section 2 we describe the RSG target selection, observation, and data reduction. In Section 3 we discuss the methods for determining the effective temperatures and metallicity. In Section 4 we compare the effective temperatures of our RSG sample with stellar evolutionary models and discuss the implications for the metallicity dependence of the mixing length. In Section 5 we conclude this work.

2. Target Selection, Observation, and Data Reduction

RSG candidates are selected from the star catalog of IC 1613 classified by Chun et al. (2015). These authors investigated the stellar populations in IC 1613 using optical (\(g, i\)) and near-infrared (\(JHK_s\)) photometry, and separated the stellar populations brighter than the tip of the red giant branch into foreground Galactic stars, supergiants, and asymptotic giant branch (AGB) stars in IC 1613 (see the text and Figure 4 in Chun et al. 2015 for details). In order to select suitable targets for MMIRS observation, we tested the slit mask configuration several times to maximize the number of observable RSGs, considering the sky positions of the RSGs across IC 1613 and distributions in the \((J-K_s, K_s)\) color–magnitude diagram (CMD). We finally select 72 targets among the 518 RSG candidates.

In the left panel of Figure 1, the selected 72 RSGs are displayed on the Very Large Array (VLA) H I map of IC 1613 (Lozinskaya et al. 2001). The RSGs in the central region of the galaxy that has the H I cavity were not chosen because of the difficulty of the slit mask configuration due to the crowdedness. In the right panel of Figure 1, the \((J-K_s, K_s)\) CMD for several stellar populations in IC 1613 classified by Chun et al. (2015) is presented. The preselected RSGs have a wide magnitude range, from 13.5 to 18.0 mag in the \(K_s\) band.

The near-infrared spectra for the 72 RSG targets have been obtained using the MMIRS instrument on the MMT telescope in the MOS mode. MMIRS has a HAWAII-2 2048 \(\times\) 2048 HgCdTe detector with a pixel scale of 0.02, which covers a 4′ \(\times\) 7′ field of view in the MOS mode. The combination of \(J\) grism and \(zJ\) filter, which provides \(J\)-band spectra spanning 0.94–1.51 \(\mu\)m, was used in the observation. Three slit masks with a slit width of 0.5 arcsec and a slit length of 7″ to achieve a low resolution of \(R \sim 2000\) were created, following the MMT mask design procedure. The spectra data were acquired during the nights of September 1, 2, and 7 in 2017 by Queue mode. Our targets were observed using four dithering patterns with \(+1.8, -1.4, +1.4,\) and \(-1.8\) arcsec offsets along the slit, and an individual exposure time of 300 seconds. We took three observation runs for each mask configuration to obtain enough signals. After the target observation, the telluric standard stars (AV) for each mask were observed at a similar airmass to our target in order to correct for telluric absorption. The log of the observation is summarized in Table 1.

Data reduction was processed by using the MMIRS data reduction pipeline (Chilingarian et al. 2015) written in the IDL language. This pipeline automatically performs flat-fielding, wavelength calibration, sky subtraction, and telluric correction using observed telluric standard stars for the MMIRS spectroscopic data. The final signal-to-noise ratios (S/N) per resolution element of the reduced spectra vary from 20 to 120, depending on the magnitudes of RSG candidates and the weather conditions. We rejected spectra with S/N less than 40, and 33 RSG candidates with an average S/N \(\approx 80\) were preselected.

The radial velocities (RVs) for the 33 RSG candidates were measured by applying a cross-correlation technique to the observed spectra in the wavelength range from 1.15 to 1.25 \(\mu\)m, where several atomic absorption lines are present and molecular lines are relatively rare. We use three template spectra: Betelgeuse and Arcturus from the NASA Infrared Telescope Facility spectral library for cool stars (Rayner et al. 2009), and a synthetic spectrum. The synthetic spectrum was generated by the local thermodynamic equilibrium (LTE) line analysis and synthetic spectrum code MOOG (Sneden 1973) with a MARCS atmospheric model (Gustafsson et al. 2008) of \(T_{\text{eff}} = 3800\) K, log \(g = -0.5\), and \([Fe/H] = -0.5\). We estimated RVs from the cross-correlation functions between the observed and three template spectra, and the final RVs were averaged. From the resulting RVs, we find that 14 RSGs having an average RV of \(-160\) km s\(^{-1}\) are hosted in IC 1613. We note that it is difficult to precisely measure the RVs due to the low resolution and S/Ns of our spectra. The resulting RVs of \(-160\) km s\(^{-1}\) do not correspond to the systemic IC 1613 velocity of \(-234\) km s\(^{-1}\) measured from the H I 21 cm line spectra of Lu et al. (1993), but are in agreement with the value.

4 https://bitbucket.org/chil_sai/mmirs-pipeline
of \(-185\) km s\(^{-1}\) for RSGs in IC 1613 found by Britavskiy et al. (2014).

### 3. Determination of Stellar Parameters

Inferring the effective temperature \((T_{\text{eff}})\) is necessary to understand the physical properties of RSGs and to confront the predictions of stellar evolutionary models, but it has been a challenging issue. Levesque et al. (2005, 2006) present comprehensive studies on the effective temperature of RSGs. They derive \(T_{\text{eff}}\) of RSGs in the Milky Way and the Magellanic Clouds by fitting the synthetic spectra generated with the MARCS atmosphere models to the TiO absorption band of the optical spectra. On the other hand, Davies et al. (2013) estimate \(T_{\text{eff}}\) of RSGs in the Magellanic Clouds using the spectral energy distributions (SEDs), finding that \(T_{\text{eff}}\) inferred from the TiO band \((T_{\text{eff, TiO}})\) is systematically lower than that from the SEDs \((T_{\text{eff, SED}})\). Davies et al. (2013) argue that the TiO band property could not reflect the exact \(T_{\text{eff}}\) of the RSGs because the relatively higher layer of the atmosphere where the TiO band forms might be significantly affected by three-dimensional effects, such as granulation. Regarding the origin of the difference between \(T_{\text{eff, TiO}}\) and \(T_{\text{eff, SED}}\), Davies & Plez (2021) recently suggested that the TiO absorption becomes stronger in the presence of a strong wind, shifting the spectral type of an RSG to a later type for a given \(T_{\text{eff}}\). Alternatively, atomic lines produced in a layer below the TiO band-forming region would be less affected by the three-dimensional effects (Davies et al. 2013; Tabernero et al. 2018). Using atomic lines to infer \(T_{\text{eff}}\) and other stellar parameters of RSGs is investigated by several studies: Calcium Triplet features (Dorda et al. 2016a, 2016b; Tabernero et al. 2018; Cicenzo & Levesque 2019), J-band technique (Gazak et al. 2014; Davies et al. 2015), and line-depth ratios of iron lines (Taniguchi et al. 2018, 2020). However, there are still some systematic offsets between the \(T_{\text{eff}}\)s derived from different methods.

In the present study, we apply the J-band technique to determine the stellar parameters of our RSG sample in IC 1613. We used the spectra ranging from 1.16 to 1.23 \(\mu\)m, where several atomic absorption lines (e.g., Fe, Mg, Si, and Ti) are present with little contamination by molecular lines, to apply the J-band technique discussed by Gazak et al. (2014) and Davies et al. (2015). To fit the observed spectra, a synthetic spectral grid is generated using the online spectrum tool\(^\text{5}\) (Kovalev et al. 2018) hosted by the Max Planck Institute for Astronomy (MPIA), for which the RSG MARCS atmospheric models and the solar-scaled chemical abundance ratio from Grevesse et al. (2007) are used. The non-LTE (NLTE) effects for several elements (e.g., Fe, Si, Ti, and Mg) are corrected (Bergemann et al. 2012, 2013, 2015). The grid covers a \(T_{\text{eff}}\) range of 3400–4400 K in increments of 100 K. The surface gravity log \(g\) ranges from \(-0.5\) to \(+1.0\) in increments of 0.5 (in cgs units), and the metallicity of [Fe/H]
from −1.5 to +1.0 dex in increments of 0.25 dex. The microturbulence (ξ) range is from 1.0 to 6.0 km s$^{-1}$ in increments of 1.0 km s$^{-1}$.

The generated synthetic spectra are compared with the observed spectra, and stellar parameters and metallicity are determined by using χ² minimization. As a first step, we fit the continuum level of both the observed and model spectra. We set wavelength points where any given synthetic spectrum within a 2–5 Å wavelength window has a maximum flux, and we calculate the ratios of the flux of the model spectra to the flux of the observed spectra at these wavelength points assuming the continuum level. The continuum correction function is then constructed by fitting the ratios with a low-order polynomial function. Outlier points with the residual of the fit larger than 3σ are rejected. The final continuum correction function is applied to the synthetic spectra to fit the continuum level of the observation. At the same time, the synthetic spectra are also convolved to match the observed line profiles and the spectral resolution.

The χ² values for all synthetic spectra are calculated, and the best model with the lowest χ² value was selected. As investigated by Gazak et al. (2014), we keep two parameters among the four stellar parameters ([Fe/H], $T_{\text{eff}}$, log g, and ξ) of the selected best model and investigate the χ² distributions by varying the remaining two free parameters (e.g., [Fe/H]$-T_{\text{eff}}$, [Fe/H]$-\log g$, etc.). In this process, we can make six χ² distribution planes with a combination of two different free parameters. For each of the six planes, we interpolate the χ² grid of the two free parameters onto a denser grid plane and take two parameters at the minimum χ² value as best-fit values. Three best-fit values for each stellar parameter were obtained from six χ² planes. The final best-fit parameters are the averages of these three values for each parameter. Figure 2 shows examples of the observed RSG spectra with the best-fit synthetic spectra.

We estimate the uncertainties in deriving stellar parameters through Monte Carlo simulations. The synthetic spectra of the final best-fit parameters are interpolated in the online spectrum tool with the correction of the NLTE effect. For each synthetic spectrum, we generate 200 noisy spectra by adding a random Gaussian noise to simulate the S/Ns of the observed spectrum. The best-fit parameters of the individual noisy spectra are calculated through our analysis, and the distributions of the minimum χ² for each parameter are investigated. The isocontour levels, which encompass 1σ around a minimum χ², are calculated, and then we take the minimum and maximum parameter values within the isocontours to obtain 1σ uncertainty in stellar parameters. We summarize the fundamental physical parameters for the 14 RSG targets in IC 1613 in Table 2.

Although previous studies of RSGs in IC 1613 are limited, we compare our stellar parameters with the results of previous studies. We find that three RSGs (star4, star11, and star12) in our RSG targets are commonly detected in previous RSG studies: IC 1613-1 and IC 1613-3 in Britavskiy et al. (2019) and V43 in Tautvaišienė et al. (2007). The cross-identified RSGs in previous studies are indicated in the note in Table 2. We find that the average difference in the effective temperature ($ΔT_{\text{eff}}$) is about 350 K, which is so large that our results seem to be inconsistent with previous results. However, we note that Britavskiy et al. (2019) derived effective temperatures of RSGs using model SEDs with a fixed metallicity of [Fe/H] = −1.0, which is much lower than the metallicity measured in this study and in Tautvaišienė et al. (2007), and also used narrow optical spectra with low S/N, which results in significant uncertainties of the SED fitting.

### 3.1. Sensitivity Test for RSG Models, Signal-to-noise Ratio, and Spectral Resolution

We found that the obtained effective temperatures of RSGs seem to be close to the edge (∼4400 K) of the model grid. The narrow grid coverage might introduce a bias into the results. A grid with a broader temperature range that fully encompasses the observed values is needed to obtain a more reliable result. Unfortunately, however, currently available RSG models are limited to a maximum $T_{\text{eff}} = 4400$ K.
| Star     | R.A. (hh:mm:ss) | Decl. (dd:mm:ss) | $J^a$ | $H^a$ | $K^a$ | S/N | $T_{\text{eff}}$ (K) | log g | [Fe/H] | $v_\text{i}$ (km s$^{-1}$) | log($L/L_\odot$) |
|----------|-----------------|------------------|-------|-------|-------|-----|---------------------|-------|--------|-----------------|----------------|
| star1    | 01:05:03.8905   | +02:05:49.704    | 15.9264 | 15.2343 | 14.9763 | 120 | 4310 ± 85 (4480)   | 0.9 ± 0.2 (0.2) | −0.74 ± 0.21 (−0.86) | 4.0 ± 0.4         | 4.629          |
| star2    | 01:04:59.4095   | +02:05:50.784    | 15.6624 | 14.9633 | 14.6693 | 120 | 4320 ± 118 (4360)  | 0.8 ± 0.3 (0.9) | −0.41 ± 0.29 (−0.61) | 3.9 ± 0.6         | 4.729          |
| star3    | 01:04:59.5798   | +02:06:06.588    | 16.1524 | 15.4603 | 15.2353 | 100 | 4270 ± 85 (4390)   | 0.9 ± 0.1 (0.9) | −0.52 ± 0.17 (−1.00) | 3.9 ± 0.4         | 4.544          |
| star4$^a$| 01:04:57.0190   | +02:04:44.400    | 16.1744 | 15.5273 | 15.2283 | 110 | 4300 ± 170 (4420)  | 0.9 ± 0.4 (0.8) | −0.38 ± 0.24 (−0.50) | 3.1 ± 0.4         | 4.531          |
| star5    | 01:04:54.7993   | +02:05:33.216    | 16.6994 | 15.9803 | 15.7313 | 100 | 4350 ± 62 (4470)   | 0.6 ± 0.7 (0.7) | −0.70 ± 0.22 (−0.86) | 3.7 ± 0.4         | 4.317          |
| star6    | 01:04:46.7303   | +02:03:38.592    | 16.2564 | 15.5903 | 15.3643 | 100 | 4190 ± 76 (4060)   | 0.6 ± 0.4 (1.0) | −0.79 ± 0.22 (−0.62) | 4.3 ± 0.4         | 4.507          |
| star7    | 01:04:57.7702   | +02:05:49.812    | 16.9254 | 16.2253 | 16.0133 | 90  | 4150 ± 228 (4420)  | 0.7 ± 0.6 (1.0) | −1.36 ± 0.24 (−0.89) | 3.1 ± 0.6         | 4.236          |
| star8    | 01:05:05.8704   | +02:09:41.796    | 16.0504 | 15.3303 | 15.0573 | 40  | 4380 ± 89 (4860)   | −0.3 ± 0.3 (−0.2) | −0.10 ± 0.25 (−0.46) | 3.9 ± 0.6         | 4.574          |
| star9    | 01:05:02.1506   | +02:10:15.888    | 16.5674 | 15.8533 | 15.5473 | 40  | 4050 ± 316 (4350)  | −0.4 ± 0.5 (0.6) | −0.36 ± 0.32 (−0.78) | 2.2 ± 2.3         | 4.364          |
| star10   | 01:05:09.6002   | +02:12:25.488    | 14.8874 | 14.1993 | 13.9483 | 50  | 4370 ± 85 (4370)   | −0.4 ± 0.4 (−0.5) | −0.58 ± 0.23 (−0.85) | 3.0 ± 0.4         | 5.048          |
| star11$^b$| 01:05:05.1288   | +02:11:54.312    | 15.1914 | 14.5893 | 14.3133 | 50  | 4360 ± 88 (4570)   | −0.3 ± 0.4 (0.8) | −0.71 ± 0.25 (−0.69) | 3.9 ± 0.4         | 4.937          |
| star12$^c$| 01:04:38.1697   | +02:06:44.712    | 16.3524 | 15.6103 | 15.3283 | 50  | 4360 ± 89 (4010)   | −0.4 ± 0.1 (0.7) | −1.02 ± 0.24 (−0.75) | 5.1 ± 0.5         | 4.449          |
| star13   | 01:04:33.1490   | +02:05:59.496    | 16.7074 | 16.0013 | 15.8023 | 50  | 4360 ± 105 (4140)  | 0.9 ± 0.2 (0.6) | −0.59 ± 0.26 (−0.72) | 4.1 ± 0.4         | 4.324          |
| star14   | 01:04:35.6905   | +02:06:07.884    | 17.3784 | 16.6543 | 16.2533 | 40  | 4120 ± 117 (4400)  | 0.9 ± 0.1 (0.9) | −0.50 ± 0.25 (−0.69) | 1.2 ± 0.2         | 4.029          |

Notes. The stellar parameters obtained from lower-mass models are indicated in parenthesis.

$^a$ IC 1613-3 of Britavskiy et al. (2019).

$^b$ V43 of Tautvaišienė et al. (2007).

$^c$ IC 1613-1 of Britavskiy et al. (2019).

$^d$ Near-infrared magnitudes come from Chun et al. (2015).
Regarding this problem, Davies et al. (2010) and Bergemann et al. (2012) noted that the model spectra between 1–5 $M_\odot$ and 15 $M_\odot$ for the same stellar parameters do not show much difference and there are small differences in NLTE abundance correction, according to which spherical MARCS models with lower mass could be used instead of 15 $M_\odot$ RSG models to derive the stellar parameters of the RSGs. Contrary to the note of Davies et al. (2010) and Bergemann et al. (2012), however, we found that there are considerable differences in the intensity of absorption lines between spectra of a low-mass star of 1 $M_\odot$ and spectra of an RSG of 15 $M_\odot$ at low metallicity (i.e., [Fe/H] = −0.7) across the J band as shown in the bottom panel of Figure 2. The spectra of the low-mass star model show stronger absorption lines than the RSG spectra, which would lead to higher temperature and lower metallicity when we use the low-mass model spectra to fit the observed RSGs. Therefore, we calculate systematic offsets in temperature and metallicity in using low-mass models to derive RSG stellar parameters. Two sets of 100 RSG reference model spectra with $T_{\text{eff}} = 4000$ K and 4300 K at IC 1613 metallicity were made, and then the stellar parameters of these spectra were estimated by using low-mass model spectra. The effective temperature range of 3500 K $\leq T_{\text{eff}} \leq$ 5000 K and a fixed microturbulence ($\xi$) of 4.0 km s$^{-1}$ were used for model spectra.

In Figures 3(a) and (b), systematic offsets in metallicity and temperature obtained from low-mass models to the RSG reference spectra are plotted as a function of S/N. We note that there is no significant trend in the calculated systematic offsets between RSG reference spectra at $T_{\text{eff}} = 4000$ and 4300 K. We find that the average temperature obtained from low-mass model spectra is systematically higher by about 130 ± 50 K than that of reference RSG models, while the metallicity is lower by about 0.2 ± 0.1 dex. This result is consistent with the predicted trend from using a low-mass model, and corrections using these offset values should be applied to the stellar parameters obtained from the low-mass model spectra.

With the correction values, we use low-mass models and derive again the stellar parameters of the observed RSGs using the same fitting process. The stellar parameters after systematic corrections (i.e., $\Delta T = 130$ K and $\Delta [\text{Fe/H}] = 0.2$) are indicated in parenthesis in Table 2. The final corrected average temperature and metallicity (i.e., $\langle T_{\text{eff}} \rangle = 4380 \pm 200$ K, $\langle [\text{Fe/H}] \rangle = −0.73 \pm 0.15$) are comparable to those $\langle T_{\text{eff}} \rangle = 4280 \pm 110$ K, $\langle [\text{Fe/H}] \rangle = −0.68 \pm 0.28$ obtained from RSG model spectra. We note that the average temperature and metallicity without corrections are higher by about 180 K and lower by 0.18 dex than those obtained from RSG model spectra, respectively. The differences in temperature and metallicity are almost consistent with the predicted systematic offsets. Therefore, we adopt and use the stellar parameters obtained from RSG models in the following analysis and figures.

Gazak et al. (2014) has tested the dependence of the inferred stellar parameters obtained by the J-band technique on the spectral resolution and S/N for the RSG spectra of solar metallicity, and shown that low resolution and/or low S/N can introduce systematic errors into the measured temperature and metallicity. Gazak et al. (2014) suggested that stellar parameters with reliable
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accuracy could be obtained from RSG spectra with $S/N > 100$ at the minimum spectral resolution of $R = 2000$. Thus we also test the sensitivity of our stellar parameters as functions of spectral resolution and $S/N$. We made sets of 60 metal-poor ([Fe/H] = $-0.7$) RSG model spectra at given resolutions ($R = 2000$, 3000, and 5000) and $S/N$ per resolution element (20, 40, 90, 130, and 170), and looked into how the retrieved stellar parameters compare to the input parameters. The average and standard deviation of the difference between the input and retrieved parameters were calculated.

Figures 3(c) and (d) show the differences in metallicity and effective temperature between input and retrieved parameters as functions of $S/N$ and resolution. The high-resolution spectra with higher $S/N$ provide more accurate effective temperatures with a small standard deviation. However, the temperature difference between the results with $S/N = 40$ and 100 at $R = 2000$ is about 80 K, while the variation between the results with $R = 2000$ and 5000 at $S/N = 40$ is about 40 K. In addition, the metallicity does not seem to be significantly changed by the resolution and $S/N$. For the spectral resolution ($R = 2000$) and the $S/N$ of our spectra, the maximum difference from the result of a higher resolution or $S/N$ would be about 0.2 dex in metallicity and 150 K in temperature. Therefore we conclude that the resolution and $S/N$ of our spectra can provide reasonable stellar parameters.

3.2. Metallicity and Temperature Distributions

We present the metallicity and effective temperature of our 14 RSG targets in IC 1613 in Figure 4, compared with those of the RSGs in the SMC given by Davies et al. (2015). The average metallicity of the RSG sample in IC 1613 is $[\text{Fe/H}] = -0.69 \pm 0.27$, which is slightly lower than the average metallicity ($[\text{Fe/H}] = -0.49 \pm 0.16$) of the SMC sample of Davies et al. (2015). This metallicity value is significantly higher than that of old and intermediate-age stellar populations in IC 1613 ($[\text{Fe/H}] \sim -1.9$ to $-1.19$; Freedman 1988b; Cole et al. 1999; Tikhonov & Galazutdinova 2002; Skillman et al. 2003; Kirby et al. 2013) but consistent with the young stellar population metallicity of $[\text{Fe/H}] = -0.69 \pm 0.09$ (Tautvaišienė et al. 2007). Berger et al. (2018) also report $[Z] = -0.69 \pm 0.24$ for blue supergiant stars in IC 1613, which are RSG precursors. Since IC 1613 has been continuously star-forming at a constant rate throughout its lifetime (Cole et al. 1999; Bernard et al. 2007; Skillman et al. 2014), the metallicity of young stellar populations compared to old and intermediate-age stellar populations is expected, as also discussed in Tautvaišienė et al. (2007).

One of the interesting results of Berger et al. (2018) is the bimodal metallicity distribution of blue supergiants and the spatial concentration of the metal-rich component in the central region of the galaxy. The metallicity distribution in our RSG sample shows a broad spread (see Figure 4). However, local peaks are also found at around $[\text{Fe/H}] \sim -0.4$ and $[\text{Fe/H}] \sim -0.7$, which are almost the same as those of Berger et al. (2018). Therefore, we divided the RSGs into two groups: seven metal-rich ($[\text{Fe/H}] > -0.65$) and seven metal-poor ($[\text{Fe/H}] < -0.65$). In the left panel of Figure 1, the metal-rich and metal-poor groups are indicated by red and blue open circles. Although the RSGs in the center of the galaxy were not observed in this study, there seems to be no spatial dependence between the metal-rich and metal-poor groups. Regarding the metallicity dependence, a nonsignificant (Sibbons et al. 2015) or slightly negative metallicity gradient (Chun et al. 2015) as a function of radial distance is reported for the intermediate-age AGB stars in IC 1613.

Stellar evolutionary models predict systematically lower RSG effective temperatures at higher metallicity for a given mixing length (see Chun et al. 2018 for a recent discussion). In the effective temperature distribution of Figure 4, we find that the average temperature of RSGs in IC 1613 is higher (by about 250 K) than that of RSGs in the SMC. Note, however, that no clear correlation between $T_{\text{eff}}$ and metallicity among our RSG sample is found. Spectroscopic data with higher resolution are necessary to find such a correlation among the RSGs in the galaxy. The trend of increasing temperature toward lower metallicity is also reported in the study of Britavskiy et al. (2019). They compared the effective temperatures of a small number of RSGs in several dwarf irregular galaxies (including IC 1613) that have different metallicity environments in the Local Group, finding a clear trend of an increasing RSG effective temperature toward lower metallicity.

Our results appear to be in contrast to the previous work from Davies et al. (2013, 2015), who find a roughly uniform temperature distribution of RSGs in the LMC and SMC. However, we have to note that they just find no systematic difference in temperature between the LMC ($4170 \pm 170$ K) and SMC ($4030 \pm 90$ K) for a small sample (9–10 RSGs) at the level of the precision of the measurements ($\sim 190$ K). Davies et al. (2018) could later find a systematic shift in spectral types and temperature for a large sample of cool supergiants in the LMC and SMC. Tabernero et al. (2018) also find a significant...
difference ($\Delta T \sim 150$ K, see Figure 3 in their paper) in the temperature distributions between the LMC and SMC for more than 400 RSGs. Although González-Torà et al. (2021) could not find a meaningful difference in temperature between the LMC ($4140 \pm 148$ K) and SMC ($4130 \pm 103$ K) because of the rather large uncertainty ($\sim 180$ K) in their temperature measurement, they find that RSGs in the WLM dwarf galaxy, which has a lower metallicity than the SMC, have a lower average $T_{\text{eff}}$ than RSGs in the SMC by about 250 K. Therefore, our finding that the average $T_{\text{eff}}$ of RSGs in IC 1613 is higher than that of SMC RSGs supports the conclusion of Davies et al. (2018), Tabernero et al. (2018), and González-Torà et al. (2021) that $T_{\text{eff}}$ of RSGs increases with decreasing metallicity. A more accurate investigation of metallicity and temperature for a larger sample of RSGs in IC 1613 is needed to confirm the metallicity dependence of the RSG temperature in environments more metal-poor than the SMC.

4. Comparison with Stellar Evolutionary Tracks

We derived the bolometric luminosities of RSGs and compared the derived temperatures and luminosities with the evolutionary tracks in a Hertzsprung–Russell (H–R) diagram. We use the near-infrared photometric magnitudes of Chun et al. (2015) in the $K$ band because the WIRCam photometry by Chun et al. (2015) provides more accurate magnitudes than those of the Two Micron All Sky Survey (2MASS, Cutri et al. 2003). The near-infrared magnitudes of WIRCam photometry are presented in Table 2. We note that the magnitudes of all RSG candidates of IC 1613 are on or below the limit of 2MASS. The bolometric magnitudes are calculated using the extinction values from Schlafly & Finkbeiner (2011), the bolometric correction relations between the $K_s$ band and $J-K_s$ for spectroscopically late-type long periodic variables (Bessell & Wood 1984), and the distance modulus of $\mu_0 = 24.291$ (Pietrzyński et al. 2006). This method is relatively insensitive to extinction as reported by Britavskiy et al. (2019). We also derived the bolometric luminosities using the bolometric correction of Davies et al. (2013), and found that the average difference in the two luminosities is about 0.005 dex.

The evolutionary tracks to compare with our RSG targets are calculated with the MESA code (Paxton et al. 2011, 2013, 2015). We follow the physical assumptions described in Section 2 of Chun et al. (2018). In short, we considered both the Schwarzschild and Ledoux criteria for convection. Since the average metallicity of RSGs in IC 1613 is comparable to or slightly lower than that of the SMC, we calculate the evolutionary tracks of the SMC-like ($Z = 0.004$) and lower ($Z = 0.002$) metallicities. For each metallicity, four different mixing length parameters are considered: $\alpha_{\text{MLT}} = 1.5, 2.0, 2.5,$ and $3.0$, which are given in units of the local pressure scale height. An overshooting parameter $f_{\text{ov}} = 0.15$, which is given in units of local pressure scale height at the upper boundary of the convective core, is used.

In Figure 5 we present the RSGs of IC 1613 on the H–R diagram compared with the evolutionary tracks at $Z = 0.004$.
and $Z = 0.002$. We also include the RSGs in the SMC of Davies et al. (2015) in the figure. As discussed in Chun et al. (2018), the evolutionary tracks of $Z = 0.004$ with $\alpha_{\text{MLT}} \approx 2.0$ for both the Schwarzschild and Ledoux criteria can reproduce the temperatures of the RSGs in the SMC. However, these tracks are systematically lower than the temperatures of the RSGs in IC 1613. The evolutionary tracks with $\alpha_{\text{MLT}} = 2.5$ are roughly compatible to the positions of the RSGs of IC 1613. For $Z = 0.002$, the evolutionary tracks with $\alpha_{\text{MLT}} = 2.0$ give effective temperatures consistent with those of observed RSGs in IC 1613.

The average luminosity of our RSG targets in IC 1613 is lower than that of the SMC. The majority of RSGs in IC 1613 are located below the 19 $M_\odot$ evolutionary track (Figure 5). This is simply because of the selection effect in our work. As shown in the CMD of Figure 1, the majority of the RSGs observed in IC 1613 have a magnitude of $K_s > 15$, and there are many bright RSG candidates that are not observed in this study. If we had a larger sample of RSGs including bright candidates over the full spatial extent of IC 1613, it would be possible to constrain $L_{\text{max}}$ or the Humphreys–Davidson limit in this galaxy.

In order to find the mixing length value that gives the best fit to the position of RSGs in the H–R diagram, the time-weighted effective temperature ($\langle T_{\text{eff}} \rangle_{\text{RSG}}$) and luminosity ($\langle L \rangle_{\text{RSG}}$) from the evolutionary tracks are calculated. We interpolate $\langle T_{\text{eff}} \rangle_{\text{RSG}}$ and $\langle L \rangle_{\text{RSG}}$ at mixing lengths from $\alpha_{\text{MLT}} = 1.5$ to 3.0 in increments of 0.1, and then compare the effective temperatures of the RSGs in IC 1613 with those of the interpolated values at a given luminosity. The $\chi^2$ value is calculated from the deviation between the observation and model temperatures, and the mixing length value with the lowest $\chi^2$ is selected as the best-fit value (see Section 4 of Chun et al. 2018 for more details on this approach). In Figure 6, the effective temperatures and luminosities of the RSGs in IC 1613 are compared with time-weighted temperatures and luminosities of the evolutionary tracks in the H–R diagram. From our $\chi^2$ minimization analysis, we find that the best fits of the Schwarzschild and

![Figure 6](image_url)
Ledoux models with $Z = 0.004$ to the observation are given by $\alpha_{\text{MLT}} = 2.3$ and 2.4, respectively. On the other hand, for $Z = 0.002$, a lower mixing length value of $\alpha_{\text{MLT}} = 2.2$ for both the Schwarzschild and Ledoux models gives the best fit to the observed data.

In Figure 7, we compare the mixing length value of IC 1613 with those of the SMC ($Z = 0.004$), LMC ($Z = 0.007$), and the Milky Way ($Z = 0.02$) from Chun et al. (2018). We assume $Z = 0.002$ and $Z = 0.004$ as the metallicity of IC 1613 because the metallicity of RSGs in this study shows a broad distribution. The mixing length values of the different galaxies calibrated by the $f_{\text{esc}} = 0.15$ models and the SED temperatures in Chun et al. (2018) were adopted. Recently, González-Torá et al. (2021) reported the effective temperatures and luminosities of RSGs in the WLM galaxy by fitting the SEDs obtained by VLT+XSHOOTER with MARCS model atmospheres. We use their temperatures and apply the same analysis in this study to obtain the calibrated mixing length value for WLM, for which we used the metallicity of $Z = 0.0014$ to calculate the MESA evolutionary models. We find that evolutionary models with mixing length of $\alpha_{\text{MLT}} = 2.1$ reproduce well the location of WLM RSGs in the H-R diagram for both Schwarzschild and Ledoux convection criteria. The results for WLM RSGs are included in Figure 7. Here we note that the metallicity and temperature of IC 1613 without the correction discussed in Section 3.1 are very close to those of WLM. Thus, the similar mixing length value to WLM is expected. If we adopt the metallicity and temperature without correction, we indeed find that $\alpha_{\text{MLT}} = 2.1$ is the best mixing length for IC 1613.

The metallicity-dependent mixing length trend found by Chun et al. (2018) becomes ambiguous by adding the results of IC 1613 and WLM in the low-metallicity regime, in particular for the Schwarzschild case. The mixing length values for IC 1613 and WLM are higher than or comparable to that of the SMC in the Schwarzschild and Ledoux cases, respectively. The uncertainties in metallicity and effective temperature of our results seem to make it difficult to find clear evidence for a metallicity-dependent mixing length in the regime of $Z \lesssim 0.004$. However, it is evident that the mixing length values for IC 1613 and WLM are still significantly lower than that of the Milky Way. More accurate temperature and metallicity measurements from a large sample of RSGs for several metal-poor galaxies are necessary to confirm the metallicity-dependent mixing length in the metal-poor regime. The metal-poor ([Fe/H] $\lesssim -0.8$) star-forming dIrr galaxies in the Local Group such as Pegasus, Sextans A, and Sextans B (e.g., Britavskiy et al. 2019) would be ideal targets for future work.

5. Conclusions and Summary

We investigate RSGs in the dwarf irregular galaxy IC 1613 in the Local Group using $J$-band spectra with a low resolution ($R \sim 2000$) obtained by the MMIRS on the MMT telescope. Among the 72 observed RSG candidates, we analyze 14 RSGs belonging to IC 1613 of which three were also studied in previous studies. The effective temperatures and metallicities of the 14 RSGs are derived by synthetic spectral fitting to the observed spectra ranging from 1.16 to 1.23 $\mu$m, where several atomic absorption lines are dominant.

We find that the average metallicity of RSGs in IC 1613 is $[\text{Fe/H}] = -0.69 \pm 0.27$, which is consistent with previous results from young massive stars but significantly higher than the metallicity of [Fe/H] $\approx -1.75$ to $-1.15$ obtained from old stellar populations in this galaxy. We find a broad metallicity distribution with weak double peaks at [Fe/H] $\approx -0.4$ and $-0.7$. However, we do not find a spatial dependence between metal-rich and metal-poor groups. On the other hand, the effective temperatures of the RSGs in IC 1613 are systematically higher by about 250 K than those of the SMC. Considering the metallicity-dependent $T_{\text{eff}}$, the higher $T_{\text{eff}}$ of IC 1613 might indirectly imply a lower metallicity than the SMC. However, we do not find a correlation between $T_{\text{eff}}$ and metallicity among our RSG sample in IC 1613. By comparing our RSG sample to evolutionary tracks of massive star evolutionary models in the H-R diagram, we find the observed RSGs have masses ranging from 9 to 23 $M_\odot$. The mixing length value for RSGs in IC 1613 calibrated with evolutionary models is $\alpha_{\text{MLT}} = 2.2$–2.4 for both Schwarzschild and Ledoux convection criteria used in the evolutionary models.

We compared this mixing length value calibrated for IC 1613 with those of the SMC ($Z = 0.004$), LMC ($Z = 0.007$), and the Milky Way ($Z = 0.02$) obtained by Chun et al. (2018). We also calibrate the mixing length value as $\alpha_{\text{MLT}} = 2.1$ for the RSGs in WLM ($Z = 0.0014$) by González-Torá et al. (2021). Although the trend of decreasing mixing length with decreasing metallicity of host galaxies weakens in the low-metallicity regime of $Z \lesssim 0.004$, it is evident that the mixing length values for IC 1613 and WLM are lower than that for the Milky Way.

Overall, the variations in effective temperatures, mixing length, and spatial distribution of RSGs with metallicity found in this study need to be further investigated for a larger sample of RSGs in IC 1613, ideally through high-resolution spectroscopic data. Furthermore, new model atmospheres with a broader range of temperature and metallicity with alpha-element enhancements are needed to obtain more accurate stellar parameters. An analogous spectroscopic analysis with...
new model atmospheres for RSGs in several metal-poor dwarf irregular galaxies in the Local Group will help constrain how the physical properties of RSGs depend on metallicity in environments more metal-poor than the SMC.

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