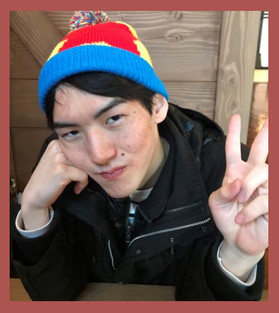

# Unbiased effective temperatures of red supergiants (RSGs) from iron absorption lines

**Daisuke Taniguchi** (The University of Tokyo) and the WINERED team

Based on Taniguchi et al. 2021 (*MNRAS*, **502**, 4210, *arXiv*: 2012.07856)

## 1. Abstract—Accurate $T_{\rm eff}$ of RSGs

The effective temperature ($T_{\rm eff}$) of red supergiants (RSGs) is important in stellar and galactic astronomy, yet some significant difficulties remain. Among spectroscopic approaches to determine $T_{\rm eff}$, the methods using atomic lines in high-resolution spectra have some advantages compared to those using molecular bands; relatively shallow atomic lines are less affected by the uncertain temperature structure in the upper atmosphere of RSGs. A promising approach is the line-depth ratio (LDR) method using ratios of line depths of two atomic absorption lines, which has been successfully applied to various kinds of late-type stars.

In this work, we established the relations between $T_{\rm eff}$ and LDR of two Fe I lines based on well-known red giant. Our LDR indicators are expected to give the consistent $T_{\rm eff}$ scale for both red giants and RSGs because the LDRs of two Fe I lines are insensitive to the surface gravity. We then measured $T_{\rm eff}$ of ten nearby RSGs including Betelgeuse observed with the WINERED near-infrared high-resolution spectrograph (0.97–1.32 μm, $R = 28,000$) to a precision of 30–70 K. Combining these $T_{\rm eff}$ with the parallaxes in the Gaia EDR3, we also determined the bolometric luminosities of the RSGs. Our effective temperatures and luminosities show good agreements with the Geneva's stellar evolution model.

## 2. Introduction1—Is $T_{\rm eff}$ using TiO molecule accurate?

- $T_{\rm eff}$ of RSGs is important to test the theory of massive stellar evolution.
- The TiO molecular band in the optical has been used to measure $T_{\rm eff}$ of RSGs (Levesque et al. 2005), but the accuracy of the resultant $T_{\rm eff}$ is still under debate.
  - The complicated structure of the upper atmosphere of RSGs including MOLsphere (Kervella et al. 2009) could bias $T_{\rm eff}$ determined using the TiO molecular band.
- Atomic absorption lines in high-resolution spectra can circumvent the uncertainty originating in the upper atmosphere of RSGs.

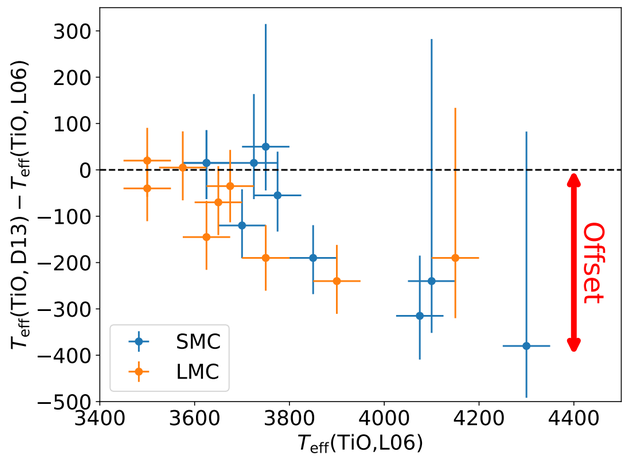


Figure 1: Comparison of $T_{\rm eff}$ of RSGs in LMC/SMC determined with the TiO molecular band by two works (Levesque et al.2006; Davies et al. 2013).

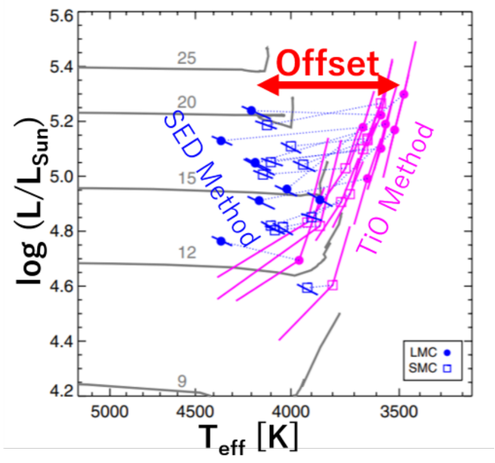


Figure 2: Comparison of $T_{\rm eff}$ of RSGs in LMC/SMC determined with two methods (Davies et al. 2013).

## 3. Introduction2—Line-depth ratio as an $T_{\rm eff}$ indicator

- Line-depth ratio (LDR) is a ratio of the depths of low- and high-EP lines.
- LDRs of two neutral iron (Fe I) lines are insensitive to the surface gravity (Jian et al. 2020), and thus LDR–$T_{\rm eff}$ relations of Fe I lines calibrated with red giants can be directly applied to RSGs.

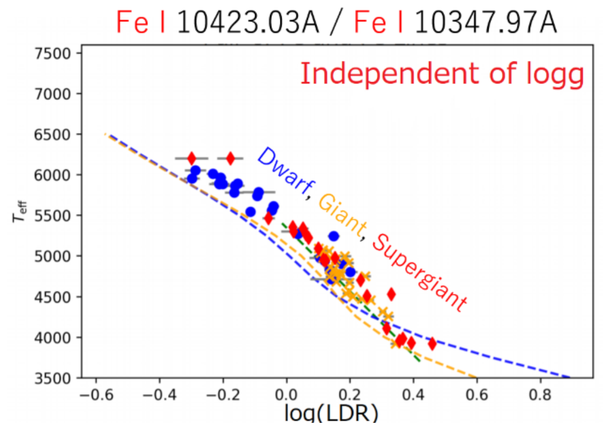


Figure 3: An LDR–$T_{\rm eff}$ relation of Fe I–Fe I pair is independent of the luminosity class (Jian et al. 2020).

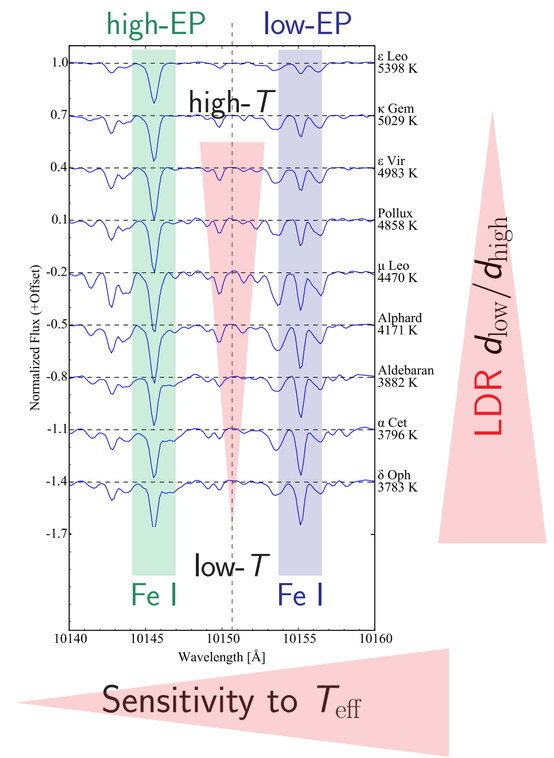


Figure 4: Spectra of red giants with decreasing $T_{\rm eff}$ (Taniguchi et al. 2018).

## 4. Observation with the WINERED spectrograph

- NIR: *z*′, *Y*, *J* bands (0.90–1.35 μm)


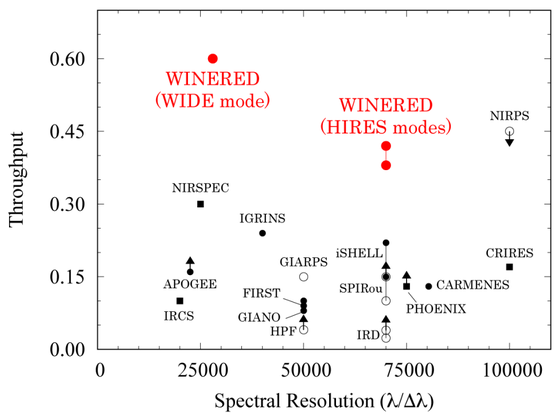


Figure 5: Performance of NIR high-resolution spectrographs (Ikeda et al. 2016; Otsubo et al. 2016).

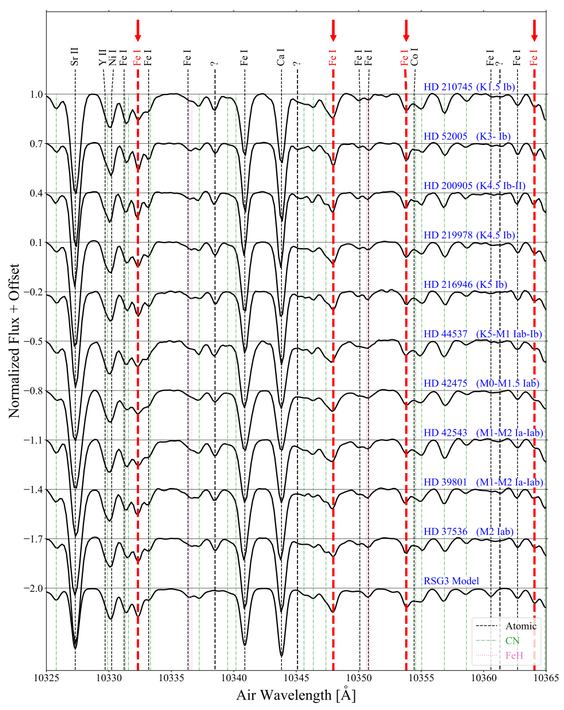


Figure 6: Sample spectra of RSGs.

Table 1: Observation log of red giants.

| Name | Sp. Type | $T_{\rm eff}$ [K] | $J$ mag | Obs. Date |
|---|---|---|---|---|
| ε Leo | G1IIIa | 5398 ± 31 | 1.63 | 2014-01-23 |
| κ Gem | G8III–IIIb | 5029 ± 47 | 2.02 | 2013-12-08 |
| ε Vir | G8III–IIIb | 4983 ± 61 | 1.31 | 2014-01-23 |
| Pollux | K0IIIb | 4858 ± 60 | −0.52 | 2013-02-28 |
| μ Leo | K2IIIbCN1Ca1 | 4470 ± 40 | 1.93 | 2013-02-23 |
| Alphard | K3IIIa | 4171 ± 52 | −0.36 | 2013-11-30 |
| Aldebaran | K5+III | 3882 ± 19 | −2.10 | 2013-02-24 |
| α Cet | M1.5IIIa | 3796 ± 65 | −0.62 | 2013-11-30 |
| δ Oph | M0.5III | 3783 ± 20 | −0.24 | 2014-01-23 |

Table 2: Observation log of RSGs.

| Name | Sp. Type | $J$mag | ObsDate |
|---|---|---|---|
| ζ Cep | K1.5Ib | 0.97 | 2015-08-08 |
| 41 Gem | K3–Ib | 2.92 | 2015-10-28 |
| ξ Cyg | K4.5Ib–II | 0.93 | 2016-05-14 |
| V809 Cas | K4.5Ib | 2.16 | 2015-10-31 |
| V424 Lac | K5Ib | 1.87 | 2015-07-30 |
| $\psi^1$ Aur | K5–M1Iab–Ib | 1.51 | 2013-02-22 |
| TV Gem | M0–M1.5Iab | 2.16 | 2016-01-19 |
| BU Gem | M1–M2Ia–Iab | 2.17 | 2016-01-19 |
| Betelgeuse | M1–M2Ia–Iab | −3.00 | 2013-02-22 |
| NO Aur | M2Iab | 2.09 | 2015-10-28 |

## 5. Results: $T_{\rm eff}$ of RSGs using the LDR method

- We calibrated 12 LDR–$T_{\rm eff}$ relations of Fe I–Fe I line pairs.
- $T_{\rm eff}$ of Betelgeuse measured by us is consistent with that measured using spectro-interferometry, which supports the validity of our method.

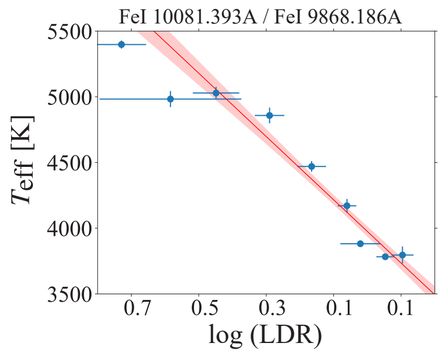


Figure 7: An example of the calibrated LDR–$T_{\rm eff}$ relation.

Table 3: $T_{\rm eff}$ measurements of Betelgeuse.

| Reference | $T_{\rm eff}$ | Method |
|---|---|---|
| This Work | 3611 ± 38 K | LDR |
| Ohnaka+11 | 3690 ± 54 K | spectro-interferometry |
| Arroyo-Torres+13 | 3620 ± 137 K | spectro-interferometry |
| Carr+00 | 3540 ± 260 K | *H*-band, CO, high-*R* |
| Levesque+05 | 3650 ± 50 K | optical, TiO band |
| Haubois+09 | 3600 ± 66 K | interferometry |
| Davies+10 | 3520 ± 160 K | *J*-band, low-*R* |

- Levesque et al. (2005) determined $T_{\rm eff}$ of RSGs in the Milky Way using the TiO method.
- Our estimates, $T_{\rm LDR}$, are consistent with theirs, $T_{\rm TiO}$(L05), but with a slope of 0.70 ± 0.14.
- This consistency indicates that the TiO method yields not strongly biased $T_{\rm eff}$ of RSGs with the solar metallicity.

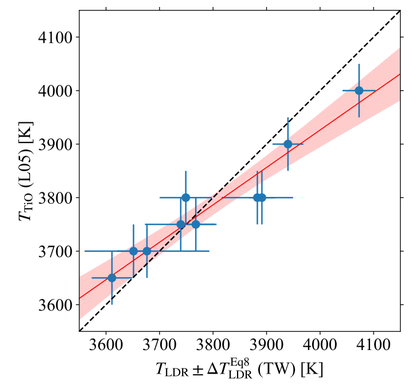


Figure 8: Comparison of $T_{\rm eff}$ by this work using the LDR and that by Levesque et al. (2005) using TiO bands.

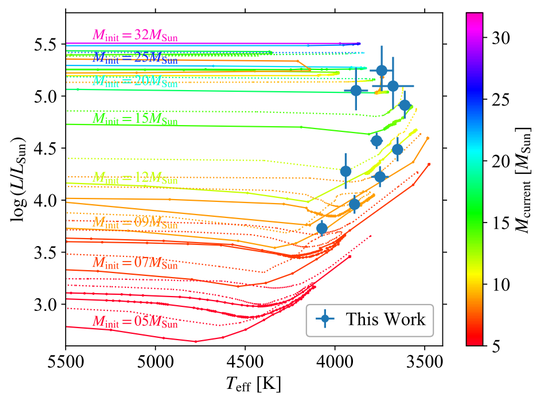


Figure 9: $T_{\rm eff}$ and log $L$ of RSGs in this work on the HR diagram.

- Using the parallax in the *Gaia* DR3 catalogue, we determined the bolometric luminosities of the RSGs.
- In the HR diagram, the distribution of our sample RSGs is well consistent with the latest Geneva's stellar evolution model with the solar metallicity (Ekström et al. 2012).
- A larger sample of RSGs would enable us to test various evolutionary models.

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