On the Performances of Estimating Stellar Atmospheric Parameters from CSST Broad-band Photometry (Postprint)

Authors: Rui-Feng Shi, Yang Huang, Xin-Yi Li and Hua-Wei Zhang

Date: 2024-05-10T00:00:00+00:00

Abstract

Deriving atmospheric parameters of a large sample of stars is of vital importance to understand the formation and evolution of the Milky Way. Photometric surveys, especially those with near-ultraviolet filters, can offer accurate measurements of stellar parameters, with the precision comparable to that from low/medium resolution spectroscopy. In this study, we explore the capability of measuring stellar atmospheric parameters from Chinese Space Station Telescope (CSST) broad-band photometry (particularly in the near-ultraviolet bands), based on synthetic colors derived from model spectra. We find that colors from the optical and near-ultraviolet filter systems adopted by CSST show significant sensitivities to the stellar atmospheric parameters, especially the metallicity. According to our mock data tests, the precision of the photometric metallicity is quite high, with typical values of 0.17 and 0.20 dex for dwarf and giant stars, respectively. The precision of the effective temperature estimated from broad-band colors are within 50 K.

Full Text

Preamble

ChinaXiv Research in Astronomy and Astrophysics, 24:045015 (13pp), 2024 April

https://doi.org/10.1088/1674-4527/ad2dbd

On the Performances of Estimating Stellar Atmospheric Parameters from CSST Broad-band Photometry

Rui-Feng Shi[1],[2], Yang Huang[1],[3],[7], Xin-Yi Li[4], and Hua-Wei Zhang[5],[6]

[1] School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China; huangyang@ucas.ac.cn
[2] South-Western Institute for Astronomy Research, Yunnan University, Kunming 650500, China
[3] CAS Key Lab of Optical Astronomy, Key Laboratory of Space Astronomy and Technology, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China
[4] Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China

Received 2023 October 17; revised 2023 December 10; accepted 2023 December 18; published 2024 April 9

Abstract

Deriving atmospheric parameters of a large sample of stars is of vital importance for understanding the formation and evolution of the Milky Way. Photometric surveys, especially those with near-ultraviolet filters, can offer accurate measurements of stellar parameters with precision comparable to that from low/medium resolution spectroscopy. In this study, we explore the capability of measuring stellar atmospheric parameters from Chinese Space Station Telescope (CSST) broad-band photometry (particularly in the near-ultraviolet bands), based on synthetic colors derived from model spectra. We find that colors from the optical and near-ultraviolet filter systems adopted by CSST show significant sensitivities to stellar atmospheric parameters, especially metallicity.

According to our mock data tests, the precision of photometric metallicity is quite high, with typical values of 0.17 and 0.20 dex for dwarf and giant stars, respectively. The precision of effective temperature estimated from broad-band colors is within 50 K.

Key words: methods: data analysis -stars: abundances -surveys

1. Introduction

The oldest stars currently observed in the Milky Way are believed to be Population II stars whose progenitors are the first stars—the so-called Population III stars (Lardo et al. 2021). It is thought that the first stars formed within hundreds of millions of years after the Big Bang through the condensation of cosmological mini-halos. Consisting of H, He, and trace amounts of Li, these mini-halos cooled via molecular hydrogen with cooling efficiency far less than that of metals. Therefore, the first stars are expected to be massive (Ishigaki et al. 2021; Zepeda et al. 2022). Metals formed during their short lives were ejected into the interstellar medium through supernova explosions, marking the first enrichment of primordial gas that led to the formation of subsequent generations of low-mass stars (Heger & Woosley 2002; Umeda & Nomoto 2002; Heger & Woosley 2010; Limongi & Chieffi 2012; Nomoto et al. 2013; Ishigaki et al. 2018).

Metallicity serves as the fossil record of a star’ s birth environment. We can thus constrain the nature of the first stars by searching for the most metal-deficient stars in the Milky Way. For example, we can constrain the baryon-to-photon ratio (Beers & Christlieb 2005) by measuring lithium abundances in very metal-poor stars. Moreover, we can determine the metallicity distribution function (MDF) of the Galaxy to explore chemical enrichment during the early stages of the Milky Way (Bonifacio et al. 2021).

The key to addressing these scientific questions is precise estimation of stellar atmospheric parameters for a large sample of stars, particularly metallicity. This has been partially achieved by spectroscopic surveys over the past few decades, which have greatly improved our understanding of the assembly history of the Galaxy. However, spectroscopic surveys are limited to samples of order 10^6 stars, far fewer than the numbers achieved by photometric surveys (like Pan-STARRS1; Chambers et al. 2016) and astrometric surveys (like Gaia; Gaia Collaboration et al. 2016). Moreover, complex selection functions must be properly accounted for in studies based on spectroscopic data (Ivezić et al. 2008; Huang et al. 2022). On the other hand, as summarized in Huang et al. (2022), the metallicities of tens of millions of stars can be precisely measured from photometric surveys with near-ultraviolet bands such as the Sloan Digital Sky Survey (SDSS, York et al. 2000), the SkyMapper Southern Survey (SMSS, Wolf et al. 2018; Onken et al. 2019), the Pristine survey (Starkenburg et al. 2017), the Stellar Abundances and Galactic Evolution Survey (SAGES, Zheng et al. 2018; Fan et al. 2023), the Javalambre Physics of the Accelerating Universe Astrophysical Survey (J-PAS, Benitez et al. 2014), the Javalambre Photometric Local Universe Survey (J-PLUS, Cenarro et al. 2019), the Southern Photometric Local Universe Survey (S-PLUS, Mendes de Oliveira et al. 2019; Whitten et al. 2021), and the Chinese Space Station Telescope (CSST, Zhan 2011). Recent efforts based on surveys with narrow/medium near-ultraviolet bands have shown that metallicity precision comparable to that from low/medium resolution spectroscopy can be achieved (e.g., Huang et al. 2019, 2022; Lin et al. 2022; Huang et al. 2023).

In this study, we focus on the CSST, a 2 m space telescope with a field of view of 1.1 deg^2. It is planned to be launched into low Earth orbit (LEO) in 2025 to carry out a large-scale sky survey covering nearly 17,500 deg^2 at high Galactic latitude ($|b| > 15°$) with a g-band limiting magnitude of approximately 26.3 (5σ point-like source). The CSST is equipped with seven filters (NUV, u, g, r, i, z, y) covering wavelengths from 2000 Å to 1.1 m. With such large sky coverage and survey depth, future CSST data will provide a revolutionary view of our Galaxy, particularly the outer halo over an unprecedented volume. Atmospheric parameters for a large sample of stars will be derived using its NUV and u bands, as well as slitless spectra (though with shallower limiting magnitude). This study attempts to explore the capability of measuring stellar atmospheric parameters from CSST broad-band colors. As a preliminary demonstration in

Figures 1 and 2, it should be specially noted that the CSST NUV and u bands show significant sensitivities to stellar surface gravity and metallicity.

This paper is organized as follows. In Section 2, we briefly introduce the adopted theoretical spectra and calculations of stellar colors. In Section 3, the sensitivity of color to stellar atmospheric parameters is explored in detail. Star classification is carried out as illustrated in Section 4. Tests on estimates of metallicity and effective temperature from the CSST filter systems are shown in Sections 5 and 6, respectively. Finally, we summarize our results and present discussions in Section 7.

2. Theoretical Spectra and Calculations of Stellar Colors

2.1. Theoretical Spectra

Theoretical spectral libraries can provide high-resolution spectra with wide parameter coverage, and these high-resolution spectra can be degraded to any lower resolution upon request. For this study, we downloaded 4542 high-resolution spectra from the PHOENIX synthetic library (Husser et al. 2013). The library covers 3000 K ≤ Teff ≤ 10,000 K, 0.0 ≤ log g ≤ 6.0, −4.0 ≤ [Fe/H] ≤ +0.5, and 0.0 ≤ [α/Fe] ≤ 0.6; the parameter coverage is shown in Figure 3 [Figure 3: see original paper].

The high-resolution spectra cover the wavelength range from 500 to 55,000 Å with a resolving power of R = 500,000 in the optical and near-infrared (3000-25,000 Å), R = 100,000 in the infrared region (25,000-55,000 Å), and $\Delta\lambda = 0.1$ Å in the UV (500-3000 Å).

2.2. Calculations of Synthetic Colors

Once the transmission curves of the filter systems (see Figures 1 and 2) and theoretical spectra are given, synthetic colors can be calculated through proper convolution (Casagrande & VandenBerg 2014). Here we adopt the AB magnitude system, which is defined as:

$$m_{\mathrm{AB}} = -2.5\log_{10}\left(\frac{\int f_{\lambda} T_{\zeta} \lambda d\lambda}{\int T_{\zeta} \lambda d\lambda}\right) - 48.60$$

where represents the bandpass ranging from λ_i to *λf, fλ* is the flux at a specific wavelength, and T__ is the throughput of a given filter. By adopting the transmission curves of CSST filters, we integrate magnitudes and their combined colors using the aforementioned theoretical spectra.

3. Sensitivity of Color to Stellar Atmospheric Parameters

Based on the above synthetic color calculations, we can now evaluate the sensitivities of CSST colors to stellar atmospheric parameters. First, stellar effective temperature can be derived from colors with two bands having separation in central wavelength (e.g., g − i, g − z, or g − y). According to previous studies (e.g., Ramírez & Meléndez 2005; Casagrande et al. 2010; Huang et al. 2015), the metallicity effect cannot be ignored in temperature determinations, though weak metallicity dependence can be found for some Teff-color relations, particularly those combining optical and near-infrared bands. Therefore, colors of g − i, g − z, and g − y are adopted for effective temperature estimates; the detailed relations will be constructed in Section 6.

Second, the color NUV − u serves as an indicator of surface gravity. As shown in Figure 4 [Figure 4: see original paper], this color shows significant sensitivity to log g between 6300 and 10,000 K. The sensitivity becomes weaker for G/K-type stars (Teff between 4500 and 6300 K), but one can still distinguish dwarf and giant stars based on NUV − u. Sensitivity is notably reduced for cool stars with Teff < 4500 K. Quantitatively, the sensitivity is calculated as the gradient of NUV − u along log g, Δ(NUV − u)/Δ log g, at a given g − i bin (equivalent to an effective temperature bin). The results are listed in Table 1 . The sensitivity from 6300 to 10,000 K is quite high, with a mean sensitivity of 0.19 mag dex^{-1} and a small scatter of 0.07 mag dex^{-1}. For G/K-type stars, the sensitivity remains quite good for giant stars but drops toward increasing log g. In summary, the color NUV − u is a good indicator for classifying dwarfs versus giants for any star hotter than 4500 K.

The CSST color (u − g) can be used to estimate stellar metallicity. Figure 5 [Figure 5: see original paper] shows the sensitivity of color to metallicity for dwarf and giant stars. It can be clearly seen that the color shows significant sensitivity to stellar metallicity across a wide temperature range for both dwarf stars (4500–8000 K) and giant stars (4500–6500 K). Quantitatively, the sensitivity is calculated as the gradient of u − g along [Fe/H], Δ(u − g)/Δ[Fe/H], at a given g − i bin. The results are listed in Table 2 . Generally, sensitivity decreases with decreasing [Fe/H] but remains quite good until [Fe/H] reaches −3.0. Overall, the sensitivity for giant stars is larger than that for dwarf stars.

We caution that the above sensitivity analysis is based on the PHOENIX synthetic spectra library, which cannot perfectly model real spectra, especially in the ultraviolet region (wavelengths shorter than 3000 Å), which is the key region for deriving stellar parameters. This represents a limitation of our sensitivity analysis. For example, a recent study by Lu et al. (2023) indicates that NUV from GALEX shows significant sensitivities to metallicity, while the CSST NUV predicted by synthetic spectra only shows moderate sensitivities to metallicity.

4. Classification of Stars

As illustrated in Section 3, the color NUV − u serves as an indicator of surface gravity. In this section, we test star classification using this color. The original parameter space coverage is too sparse (0.5 dex for log g). We therefore integrate the theoretical spectra to a step of 0.05 dex using the PHOENIX high-resolution library.

We focus primarily on the classification of FGK-type stars (4500–6600 K) in this work. To simulate realistic conditions, we adopt the observational surface gravity distribution (equivalent to the luminosity function) from stellar samples in LAMOST DR8 (http://www.lamost.org/dr8/v2.0/catalogue). The log g distribution shown in Figure 6 [Figure 6: see original paper] is used to re-sample the number of theoretical spectra and their colors. Furthermore, we enlarge our sample by repeated sampling five times.

There are 13,916 stars in our final sample (2,177 giant stars with log g < 3.5 and 11,739 dwarf stars with log g ≥ 3.5), as shown in Figure 7 [Figure 7: see original paper]. To select giant stars with minimal contamination from dwarf stars, we empirically define color cuts that roughly follow the 60% isonumber ratio in the contour. This yields:

$$(\mathrm{NUV}-u) > 0.5 \times (g-i) + 0.5$$

With these cuts, 1,069 stars are selected as giant stars (with 815 dwarf stars as contamination). The completeness of the selected giant stars is therefore around 49% (1,069/2,177), along with a purity of 57% (1,069/1,884).

Dwarf stars are selected with the opposite color cuts:

$$(\mathrm{NUV}-u) \leq 0.5 \times (g-i) + 0.5$$

With these cuts, 10,924 stars are selected as dwarf stars (with 1,108 giant stars as contamination). This means the completeness of the selected dwarf stars is around 93% (10,924/11,739), along with a purity of 91% (10,924/12,032).

We note that similar efforts have been explored using colors from the SDSS and SkyMapper surveys (e.g., Huang et al. 2019; Zhang et al. 2021).

5. Tests on Performances of Estimating Metallicity

The main purpose of this section is to determine how accurately metallicity can be measured from CSST broad-band colors. The original parameter space coverage is too sparse (0.5 dex for [Fe/H] ≥ -2.0, 1 dex for [Fe/H] < -2.0). We therefore integrate the theoretical spectra to a step of 0.05 dex.

We then construct metallicity-dependent stellar loci of u $-$ g versus g $-$ i for metallicity estimation. To achieve realistic stellar loci, the observational surface gravity distribution shown in Figure 6 is again used to re-sample the number of theoretical spectra and their colors. We classify stars into two categories: dwarf stars with log g $\geq$ 3.5 and giant stars with log g $<$ 3.5. The first and most important step is to construct the metallicity-dependent stellar loci. As shown in Figure 8 [Figure 8: see original paper], sequences for different metallicities ranging from [Fe/H] = −4 to [Fe/H] = +0.5 can be clearly seen for both dwarf and giant stars. Similar to previous studies (Yuan et al. 2015; Huang et al. 2022; Lin et al. 2022; Huang et al. 2023), third-order 2D polynomials are adopted to fit the color (u − g) as a function of (g − i) and [Fe/H] for dwarf and giant stars, respectively:

$$(u-g) = a_0 + a_1 x + a_2 y + a_3 x^2 + a_4 xy + a_5 y^2 + a_6 x^3 + a_7 x^2 y + a_8 x y^2 + a_9 y^3$$

where x denotes (g − i) and y denotes [Fe/H]. Three-sigma clipping is applied during the fitting process, and the fit coefficients are listed in Table 3 .

Using the empirical stellar loci defined above, a maximum-likelihood approach is adopted to derive metallicity estimates. For a given star, the likelihood is expressed as:

$$\mathcal{L} = \exp\left[-\frac{(c_{\mathrm{PHOE}} - c_{\mathrm{pred}})^2}{2\sigma_c^2}\right]$$

where c_{PHOE} = (u − g) is the color calculated using PHOENIX spectra, assumed to be an independent Gaussian variable; c_{pred} is the same color predicted from our metallicity-dependent stellar loci (i.e., Equation (8)). The value of [Fe/H] is varied from −4.0 to +0.5 in steps of 0.05 dex when predicting (u − g). With this likelihood function, the best-fit color (u − g) can be derived for each star, and the [Fe/H] value corresponding to this best-fit color is taken as the predicted [Fe/H].

It is worth noting that the applicable range of (g − i) in the current method is 0.26–1.24 for dwarf stars and 0.53–1.24 for giant stars. Moreover, upper and lower limits of [Fe/H] in color (u − g) are defined for various (g − i) bins.

CSST, as a planned large-scale deep survey, demonstrates powerful capability for measuring stellar atmospheric parameters, as supported by our mock data tests. It can be seen that predicted metallicity from our metallicity-dependent stellar loci is in good agreement with metallicity from PHOENIX spectra for [Fe/H] > −2 for both dwarf and giant stars, with typical scatters around 0.17 dex and 0.20 dex, respectively.

For dwarf stars (as shown in Figure 9 [Figure 9: see original paper]), the precision of the predicted metallicity is 0.14 dex if colors u − g and g − i have a random error of 0.001 mag. Even if the color error increases to 0.015 mag, the scatter remains smaller than 0.21 dex, which is comparable to that of medium-resolution spectroscopy. Although the scatter becomes larger with increasing color error, the metal-rich parts ([Fe/H] > −2) still show excellent agreement with the true values.

Figure 10 [Figure 10: see original paper] shows the results for metallicity estimation in giant stars. The scatter is smaller than 0.23 dex when the random color error lies within 0.015 mag, though slightly larger than that for dwarf stars under the same color error. Good agreement persists even under a color error of 0.025 mag.

Correspondingly, using the tool "Exposure time calculator for space telescope," the g-band limiting magnitudes under various color errors are derived, as listed in Table 4 . We expect the metallicity estimate to be better than 0.20 dex for stars with g-band magnitude down to 20.8 (color error smaller than 0.01 mag).

6. Tests on Performances of Estimating Effective Temperature

In this section, we perform tests on estimating effective temperature. Similar to Section 5, the essential step is to construct metallicity-dependent Teff–color relations. To accomplish this, second-order 2D polynomials are adopted to fit the data points for dwarf and giant stars, respectively (Figure 11 [Figure 11: see original paper]):

$$\theta_{\text{eff}} = b_0 + b_1 x + b_2 y + b_3 x^2 + b_4 xy + b_5 y^2$$

where _{eff} = 5000/Teff, x denotes (g − i), and y denotes [Fe/H]. Three-sigma clipping is applied in the fitting process. The fit coefficients are listed in Table 3 .

The performance results for estimating effective temperature from g − i color are shown in Figures 12 [Figure 12: see original paper] and 13 [Figure 13: see original paper]. High precision in effective temperature is achieved for CSST broad-band photometry, with typical values around 48 K and 47 K for dwarf and giant stars, respectively. For dwarf stars, the precision of the predicted effective temperature lies within 50 K when the random color error is smaller than 0.01 mag. Even for the maximum color error in our mock data tests, the precision remains high, with a value around 70 K. For giant stars, the precision could be slightly better, remaining smaller than 47 K even with a random color error of 0.01 mag. This again demonstrates the powerful capability of measuring stellar atmospheric parameters from the CSST survey.

Moreover, tests on estimating effective temperature from g − z and g − y colors are also performed using similar metallicity-dependent Teff–color relations, as described by Equation (10). The fit coefficients are listed in Table 5 . Figures 14 [Figure 14: see original paper] and 15 [Figure 15: see original paper] show comparisons between Teff predicted from g − z color and the true Teff for dwarf and giant stars, respectively. Good agreement is clearly seen. Compared to Teff predicted from g − i color, Teff predicted from g − z color achieves higher precision.

Figures 16 [Figure 16: see original paper] and 17 [Figure 17: see original paper] show comparisons between Teff predicted from g − y color and the true Teff for dwarf and giant stars, respectively. The precision of predicted Teff is further improved, with typical values around 29 K for both dwarf and giant stars. Therefore, for future Teff estimates from the CSST survey, we recommend using the g − y color as the priority.

It is worth noting that uncertainties from photometric calibration and reddening correction are not taken into account in the above analysis. Moreover, as discussed in Section 3, we may not be making full use of the power of CSST broad bands, especially the NUV filter, due to the imperfect performance of the PHOENIX theoretical spectra. In the near future, we will continue to address these shortcomings to present a more realistic analysis of CSST broad bands for deriving stellar parameters.

Finally, we release a code to estimate stellar atmospheric parameters ([Fe/H], Teff) for CSST. Figure 18 [Figure 18: see original paper] shows the flowchart of our code.

7. Summary

The sensitivity of CSST broad-band colors to stellar atmospheric parameters (metallicity [Fe/H], surface gravity log g) is evaluated using synthetic colors integrated from model spectra. The results show that colors from the optical and near-ultraviolet filter systems adopted by the CSST survey exhibit significant sensitivities to stellar atmospheric parameters, particularly metallicity. The sensitivity of color to metallicity is higher for giant stars than for dwarf stars, although with slightly larger scatter.

According to our mock data tests, dwarf stars can be distinguished from giant stars. CSST can provide accurate stellar metallicity and effective temperature estimates for stars with g-band magnitude down to 20.8, with high precision of around 0.20 dex and 50 K, respectively. It is inspiring that the assembly history of the Milky Way can be further revealed using such a large sample of stars with accurate estimates of stellar atmospheric parameters.

Acknowledgments

We acknowledge the science research grants from the China Manned Space Project with No. CMS-CSST-2021-A08. Y.H. acknowledges the NSFC for grant Nos. 11903027 and 11833006 and the National Key R&D Program of China for grant No. 2019YFA0405503. H.W.Z. acknowledges the NSFC for grant Nos. 11973001, 12090040, and 12090044, the National Key R&D Program of China for grant No. 2019YFA0405504, and the science research grants from the China Manned Space Project with No. CMS-CSST-2021-B05.

ORCID iDs

Rui-Feng Shi https://orcid.org/0009-0000-6932-7894

References

Beers, T. C., & Christlieb, N. 2005, ARA&A, 43, 531
Benitez, N., Dupke, R., Moles, M., et al. 2014, arXiv:1403.5237
Bonifacio, P., Monaco, L., Salvadori, S., et al. 2021, A&A, 651, A79
Casagrande, L., Ramírez, I., Meléndez, J., et al. 2010, A&A, 512, A54
Casagrande, L., & VandenBerg, D. A. 2014, MNRAS, 444, 392
Cenarro, A. J., Moles, M., Cristóbal-Hornillos, D., et al. 2019, A&A, 622, A176
Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, arXiv:1612.05560
Fan, Z., Zhao, G., Wang, W., et al. 2023, ApJS, 268, 9
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2016, A&A, 595, A2
Heger, A., & Woosley, S. E. 2002, ApJ, 567, 532
Heger, A., & Woosley, S. E. 2010, ApJ, 724, 341
Huang, Y., Beers, T. C., Wolf, C., et al. 2022, ApJ, 925, 164
Huang, Y., Beers, T. C., Yuan, H., et al. 2023, ApJ, 957, 65
Huang, Y., Chen, B. Q., Yuan, H. B., et al. 2019, ApJS, 243, 7
Huang, Y., Liu, X. W., Yuan, H. B., et al. 2015, MNRAS, 454, 2863
Husser, T. O., Wende-von Berg, S., Dreizler, S., et al. 2013, A&A, 553, A6
Ishigaki, M. N., Hartwig, T., Tarumi, Y., et al. 2021, MNRAS, 506, 5410
Ishigaki, M. N., Tominaga, N., Kobayashi, C., & Nomoto, K. 2018, ApJ, 857, 46
Ivezić, Ž., Sesar, B., Jurić, M., et al. 2008, ApJ, 684, 287
Lardo, C., Mashonkina, L., Jablonka, P., et al. 2021, MNRAS, 508, 3068
Limongi, M., & Chieffi, A. 2012, ApJS, 199, 38
Lin, J., Casagrande, L., & Asplund, M. 2022, MNRAS, 510, 433
Lu, X., Yuan, H., Xu, S., et al. 2024, ApJS, 271, 26
Mendes de Oliveira, C., Ribeiro, T., Schoenell, W., et al. 2019, MNRAS, 489, 241
Nomoto, K., Kobayashi, C., & Tominaga, N. 2013, ARA&A, 51, 457
Onken, C. A., Wolf, C., Bessell, M. S., et al. 2019, PASA, 36, e033
Ramírez, I., & Meléndez, J. 2005, ApJ, 626, 446
Starkenburg, E., Martin, N., Youakim, K., et al. 2017, MNRAS, 471, 2587
Umeda, H., & Nomoto, K. 2002, ApJ, 565, 385
Whitten, D. D., Placco, V. M., Beers, T. C., et al. 2021, ApJ, 912, 147
Wolf, C., Onken, C. A., Luvaul, L. C., et al. 2018, PASA, 35, e010
York, D. G., Adelman, J., Anderson, J. E. J, et al. 2000, AJ, 120, 1579
Yuan, H., Liu, X., Xiang, M., Huang, Y., & Chen, B. 2015, ApJ, 799, 134
Zepeda, J., Rasmussen, K. C., Beers, T. C., et al. 2022, ApJ, 927, 13
Zhan, H. 2011, SSPMA, 41, 1441
Zhang, R.-Y., Yuan, H.-B., Liu, X.-W., et al. 2021, RAA, 21, 319
Zheng, J., Zhao, G., Wang, W., et al. 2018, RAA, 18, 147

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.