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The Lines are NOT Fine:

Measuring Vanadium Abundances in M Dwarfs from Hyperfine-Split Lines

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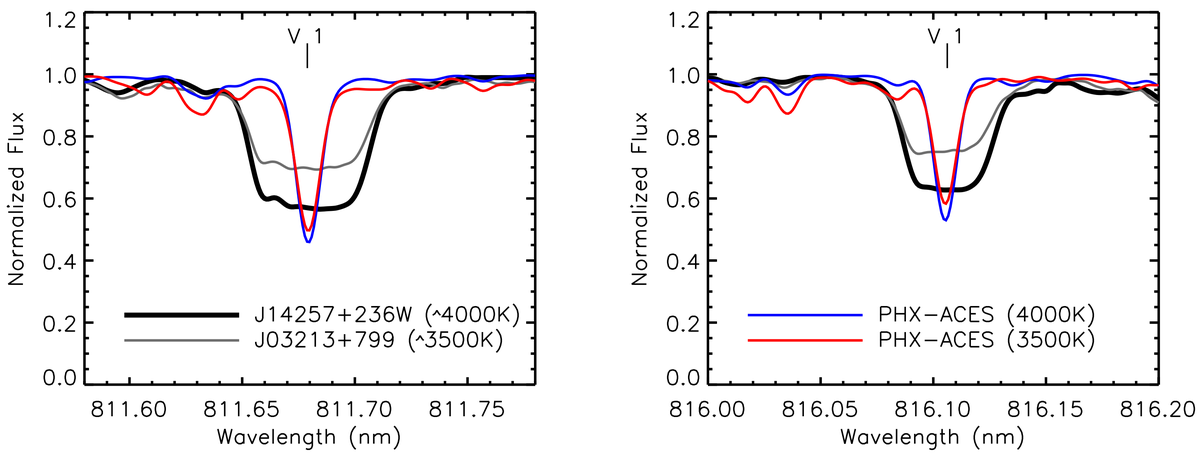
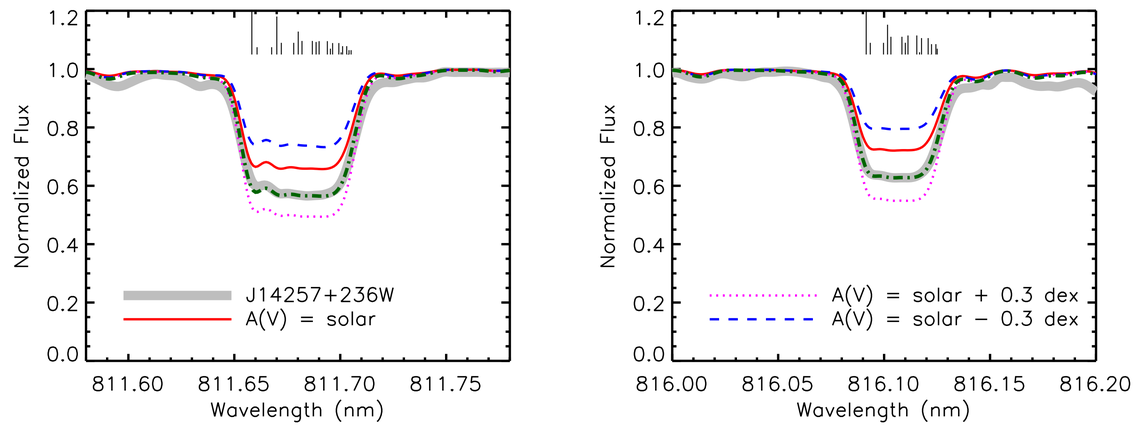
Abstract: There exists a **number of notable neutral vanadium (V I) lines** in the relatively clean 800–900 nm wavelength region of M dwarfs. In high-resolution spectra, these lines have clear presentations and distinctive broad and flat bottoms, a result of **hyperfine splitting (HFS)**. Using the latest atomic data, including HFS components, we model these V I lines in CARMENES spectra and use them to **measure robust V abundances for 140 nearby early M dwarfs** in the CARMENES-GTO sample. Their [V/Fe] vs [Fe/H] pattern is consistent with local FG-type dwarfs. The relative ease of measurement and close relationship with iron makes **V abundance a potential metallicity indicator for M dwarfs**. We also suggest that **neglecting to model HFS could largely explain a systematic trend between [V/Fe] and T_{eff}** found in previous elemental abundance studies of K dwarfs. Our work highlights **rich opportunities for chemical analysis of cool stars** afforded by high-quality spectra redward of visible.

1. 'Square buckets': neutral vanadium lines in M dwarfs



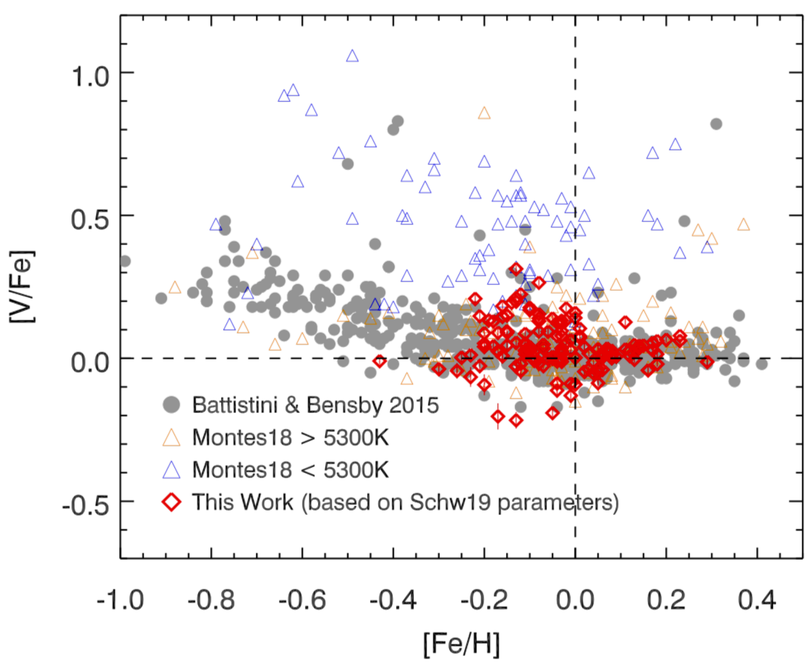
A number of neutral vanadium (V I) lines stand out in high-resolution M dwarf spectra between 800 and 900nm because they are very strong and broad and look like 'square buckets'. Their profiles show severe mismatches with standard model spectra libraries. **Black** and **grey**: CARMENES data spectra (R~96400) for M dwarfs with T_{eff} ~ 4000 K and 3500 K. **Blue** and **red**: PHOENIX-ACES model spectra [1] for T_{eff} = 4000 K and 3500 K.

2. They are 'broadened' by hyperfine splitting (HFS)



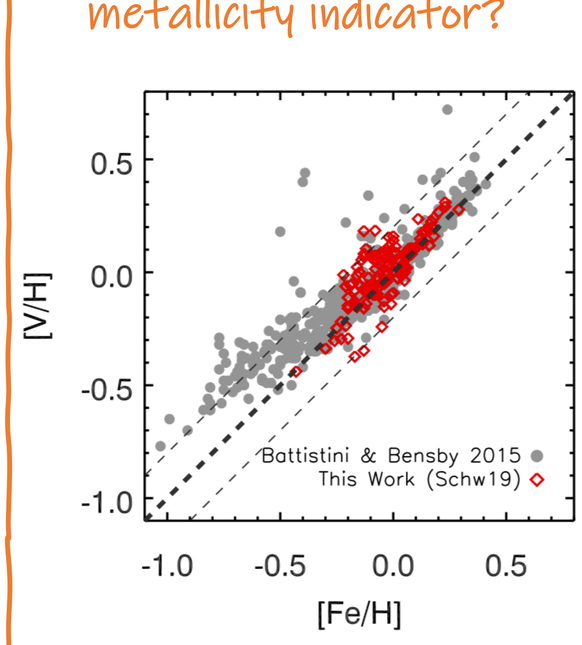
Including an HFS line list (now available via VALD3 [2]) in the synthetic model spectra, these V I lines can be reproduced very well and show strong sensitivity to abundance. **Thick grey**: CARMENES spectra for M dwarf with T_{eff} ~ 4000 K; **red**, **magenta**, **blue**: model spectra with [V/H] = solar, +0.3, and -0.3; **green**: best-fit [V/H] = +0.23; **black vertical lines**: HFS components (scaled to relative strengths). For modelling, we use iSpec [3] with MARCS atmospheres and Turbospectrum radiative transfer.

3. V abundances for 140 early M dwarfs



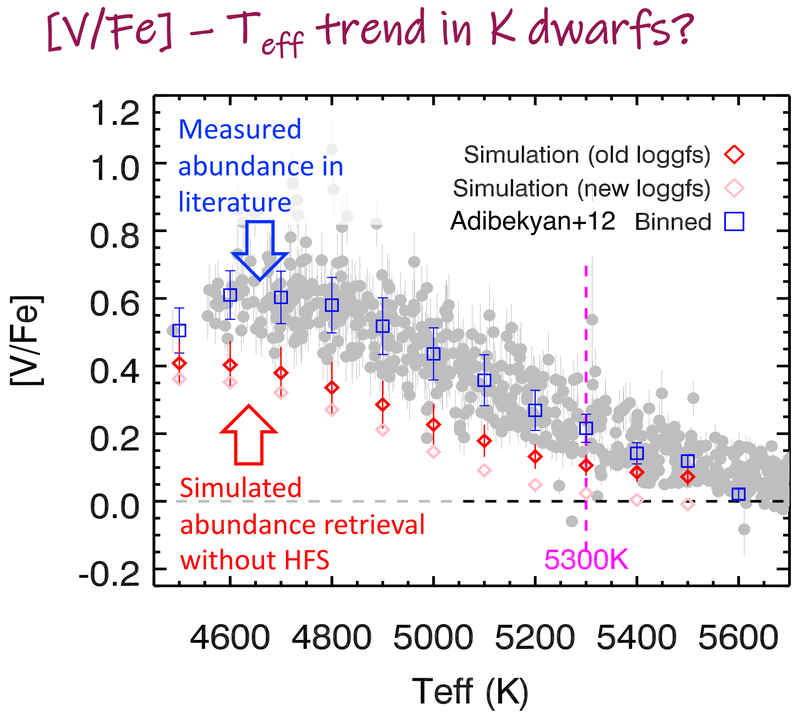
We use direct spectral synthesis fits to 9 – 13 hyperfine-split V I lines to measure the V abundances of 140 M dwarfs with T_{eff} > 3400K in the CARMENES-GTO sample. Typical line-to-line scatter is ~0.05 dex (mean stdev: 0.01 – 0.02). Fundamental stellar parameters are fixed to [4]. The fitted [V/H] is relatively insensitive to the stellar parameters. The [V/Fe]-[Fe/H] pattern of the M dwarfs (**red**) agrees with local FG dwarfs [e.g., 5, 6] (**grey**, **orange**) but disagrees with local K dwarfs [e.g., 6] (**blue**).

4. [V/H]: a novel metallicity indicator?



M dwarf metallicities are difficult to determine to 0.1 dex precision [e.g., 7]. V is an iron-peak element whose abundance closely tracks iron. A tight (stdev ≲0.1dex) correlation between [V/H] and [Fe/H] may be exploited as an alternative metallicity indicator wherever V can be easily measured (e.g., in the 811.67nm line).

5. HFS: plausible explanation for the [V/Fe] – T_{eff} trend in K dwarfs?



Several chemical studies of FGK dwarfs observed that [V/Fe] increases from ~0 to >0.6 dex when T_{eff} decreases from 5300 K to ~4500 K, also growing in line-to-line scatter [e.g., 6,8] (**grey**, **blue**). For input [V/Fe] = 0, our mock abundance retrievals on the same line regions without an HFS line list qualitatively reproduces this trend (**red**), suggesting that the correlation is likely a result of the studies' neglect to model HFS.

References

[1] Husser et al., 2013, A&A, 553, A6. [2] Pakhomov et al., 2019, Astronomy Reports, 63, 1010. [3] Blanco-Cuaresma, 2019, MNRAS, 486, 2075. [4] Schweitzer et al., 2019, A&A, 625, A68.
[5] Battistini & Bensby, 2015, A&A, 577, A9. [6] Montes et al., 2018, MNRAS, 479, 1332. [7] Souto et al., 2020, ApJ, 890, 133. [8] Adibekyan et al., 2012, A&A, 545, A32.

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