Optical and Near-infrared Radial Velocity Content of M Dwarfs: Testing Models with Barnard’s Star

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Abstract

High-precision radial velocity (RV) measurements have been central in the study of exoplanets during the last two decades, from the early discovery of hot Jupiters, to the recent mass measurements of Earth-sized planets uncovered by transit surveys. While optical RV is now a mature field, there is currently a strong effort to push the technique into the near-infrared domain (chiefly Y, J, H, and K bandpasses) to probe planetary systems around late-type stars. The combined lower mass and luminosity of M dwarfs leads to an increased reflex RV signal for planets in the habitable zone compared to Sun-like stars. The estimates on the detectability of planets rely on various instrumental characteristics but also on a prior knowledge of the stellar spectrum. While the overall properties of M dwarf spectra have been extensively tested against observations, the same is not true for their detailed line profiles, which leads to significant uncertainties when converting a given signal-to-noise ratio to a corresponding RV precision as attainable on a given spectrograph. By combining archival CRIRES and HARPS data with ESPaDOnS data of Barnard’s star, we show that state-of-the-art atmosphere models over-predict the Y- and J-band RV content by more than a factor of ~2, while under-predicting the H- and K-band content by half.

Key words: techniques: radial velocities – instrumentation: spectrographs – methods: data analysis – stars: low-mass

1. Introduction and Context

Radial velocity (RV) measurements at an ever increasing precision have been central to our quest to find planets around other stars. The first exoplanet around a Sun-like star, 51 Pegasi, was found through precise monitoring of its parent star velocity (Mayor & Queloz 1995) using the ELODIE spectrograph. Over the first decade, following the discovery of 51 Pegasi, RV monitoring accounted for 88% of exoplanet discoveries. With the launch of Corot and Kepler, and thanks to a number of ground-based surveys, the bulk of exoplanet discoveries now come from transit detection. The upcoming launch of the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2014) will provide an even larger sample of short-period transiting planets around relatively bright stars over most of the sky. Ground-based RV follow-up of TESS discoveries will require a significant investment of observing time. RV searches continue to play a crucial role in the field by discovering the majority of the planets in the close solar neighborhood, which are not transiting, and in identifying long-period planets, to which transit searches are not sensitive due to the decreasing likelihood of transits on wide orbits and sparseness of transits in time. RV is the prime tool to establish planetary system architectures out to a few astronomical units. In most cases, RV monitoring is the only tool currently available to confirm transiting planets, measure their masses, and ultimately constrain their bulk density. Furthermore, RV measurements can lead to the discovery of additional non-transiting planets in systems with a transiting companion (Cloutier et al. 2017).

Only a handful of transiting Earth-sized planets orbiting Sun-like stars are known due to the rarity of their occurrence (once a year) and shallow depth. No such planet has been found by RV surveys and none of the transiting ones can be followed-up with current RV instrumentation due to the inherent high precision required (e.g., the Earth produces an RV reflex motion on the Sun with a semi-amplitude of only 10 cm s⁻¹). Characterization of Earth-like planets is one of the major goals of exoplanet science in the near future, and M dwarfs represent a short-cut for finding such planets with existing technologies. The interest of M dwarf in the quest of habitable worlds is many-fold. First, despite having a very incomplete census of nearby M-dwarf planets, transit surveys provide strong constraints on the occurrence rate of planets around early M dwarfs. Within the Kepler data set, Dressing & Charbonneau (2015) derived an occurrence rate for 1–4 R⊕ planets of 2.5 per star, including an average of 0.56 Earth-sized planet (1–1.5 R⊕) within a 50-day orbit around Kepler M dwarfs. This result contrasts with the absence of Jupiter-mass planets in RV searches around early M dwarfs (occurrence <1% for 10³–10⁴ M⊕; Bonfils et al. 2013). Neptune-sized and smaller planets appear to abound, implying that the bulk of the nearest exoplanets orbit M dwarfs. This abundance is exemplified by the discovery of an Earth-mass planet in the temperate zone of our closest stellar neighbor: Proxima Centauri (Anglada-Escudé et al. 2016). Besides being ubiquitous, M dwarf planets also have a number of observational advantages easing their study compared to planets orbiting Sun-like stars. The smaller radius of M dwarfs (0.1–0.5 R⊙) leads to much deeper transit depths for a

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5 http://exoplanets.org
given planetary radius; this not only makes the discovery of transiting planets more likely, but also facilitates transit spectroscopy. Planets around M dwarfs in the solar neighborhood will be also the first priority target to characterize atmosphere in coupling high contrasts imaging and high spectral resolution capacity of ELT (Snellen et al. 2015) or even 10-m telescopes (Lovis et al. 2016). The smaller radius and lower temperature (2500–3900 K; Rajpurohit et al. 2013) leads to orbital separation for habitable zone planets in the range of 0.017–0.2 au, which increases the likelihood of transit and leads to short orbital periods (<100 days) for these type of planets. Importantly, the tighter orbit and lower-mass primary (0.07–0.5 M_☉) lead to a much larger RV signal than for a planet around a Sun-like star. An Earth-mass planet around a field M5V star (~0.15 R_☉, ~0.1 M_☉, 3200 K) receiving the same illumination as the Earth has an orbital separation of 0.04 au and an orbital period of 9 days and induces an RV signal of 1 m s⁻¹. Signals at this level can be detected by state-of-the-art velocimeters such as HARPS (Pepe et al. 2000) or Keck HIRES (Vogt et al. 1994). The main drawback facing existing precision radial velocity (PRV) spectrograph arises from the faintness of M dwarfs at optical wavelengths. The HARPS M dwarf planet search (Bonfils et al. 2013) yielded ~m s⁻¹ RV precision in 15 minutes for stars brighter than V = 10. Despite the fact that M dwarfs largely outnumber Sun-like stars in the solar neighborhood, there are only 116 M dwarfs this bright, mostly of early (<M4) spectral types (see Section 4.4 in Figueira et al. 2016 for a discussion of the local M dwarf sample).

The best strategy to study a large sample of M dwarf HZ planets is to obtain RV measurements with m s⁻¹ level, or better, precision in the wavelength domains where the spectral energy distribution of these objects peaks, namely the near-infrared (nIR; 1–2.4 μm). A number of high-precision RV spectrographs will be commissioned in the near future (e.g., SPIRou, Artigau et al. 2014b; IRD, Tamura et al. 2012; HPF, Mahadevan et al. 2014; NIRPS, Bouchy et al. 2017) or have recently seen first light at the telescope (CARMENES-IR, Quirrenbach et al. 2010). Other instrument designs favor a far-red design (0.7–1.0 μm), which is competitive with nIR instruments through most of the M dwarf regime except for very-late-M dwarfs (e.g., Maroon-X, PARAS, CARMENES-Optical; Chakraborty et al. 2014; Seifahrt et al. 2016). The expected sensitivity of an RV spectrograph depends on its ability to detect the induced RV Doppler effects at a level orders of magnitudes smaller than the instrument’s resolution or the natural width of stellar features.

In terms of instrumental development, there are numerous stability and calibration challenges (see the review by Fischer et al. 2016 and references therein), but with intrinsically stable and well-characterized instruments, this floor in the performances can be significantly smaller than astrophysical RV jitter and can be limited due to the finite signal-to-noise ratio (S/N) of observations. In the ideal case of a slightly active, slowly rotating star, the limitation is determined by the RV information content of the stellar spectra and the S/N with which it is achieved, and the purpose of the present paper is to assess this limitation for various instrument setups. Connes (1985) and Bouchy et al. (2001) provide a formal framework for determining the ultimate RV precision that can be reached for a given spectrum and S/N.

Modeled M dwarf spectra can be used to derive expected sensitivities for existing and upcoming nIR precision radial velocity (PRV) spectrographs (e.g., Reiners et al. 2010; Rodler et al. 2011; Figueira et al. 2016). As the RV content of a spectrum scales as the resolution to the power of 3/2 (Pepe et al. 2014), modest errors in stellar line profiles or incomplete line lists may lead to significant errors in the estimation of the RV content of the underlying spectrum. For the current analysis, we used the spectra of Barnard’s star in the CRIRES-POP spectral library (Lebzelter et al. 2012). These observations cover the Y, J, H, Ks, L, and M bands; of specific interest here being the spectral domain, shortward of 2.38 μm, that is amenable to m s⁻¹-level precision velocimetry. While the 3–5 μm domain contains strong molecular bandpasses that could be of interest for velocimetry, it also suffers from strong telluric absorption and increased thermal background (see Smette et al. 2015, Figure 1); due to these challenges and the current lack of effort to develop mid-IR velocimetry, we will not attempt to estimate the relative importance of this wavelength domain. Until recently, this was the only M dwarf with a published near-infrared coverage at very high (Δλ/Δλ > 70000) resolution. The recent publication of CARMENES-optical and near-infrared spectrum (Reiners et al. 2017) of 324 M dwarfs over the 0.52–1.71 μm domain (g through most of H band) largely fills this gap. The present data set also includes the K band (1.95–2.40 μm), which is covered by a few pRV spectrograph (SPIRou, GIANO, CRIRES+). None of the currently publicly available high-resolution M dwarf spectrum has been cleaned from telluric absorption through either the near-simultaneous observation of hot stars and/or the combination of exposures taken at varying barycentric velocity.

In an attempt to obtain a realistic estimate of the RV content of M dwarfs and assess the usefulness of existing models, we present a comparison between the spectrum of Barnard’s star observed with HARPS, ESPaDOnS, CRIRES (Pepe et al. 2000; Kaeufl et al. 2004; Donati et al. 2006), and PHOENIX-ACES models over the optical and near-infrared domain (0.4–2.35 μm).

We present the properties of Barnard’s star in Section 2 and the data set used to determine its RV content in Section 3.
Results and discrepancies between the observed and model RV content are presented in Section 4 while Section 5 discusses the implication of these results for nIR PRV instruments.

2. Barnard’s Star Properties

Barnard’s star, at 1.8 pc from the Sun, is the second closest M dwarf after Proxima Centauri, and it holds the distinction of being the star with the highest apparent proper motion (Barnard 1916). As a 7–10 Gyr thick-disk star, it is expected to be a slow rotator; while its rotation period has not been unambiguously established, HST guider photometry points toward a period of ~130 days (Benedict et al. 1998). This period is in very good agreement with the estimation of Astudillo-Defru et al. (2017) through a determination of $\log R'_{HK} = -5.7$. With a $R_\odot$ radius, this corresponds to a $v \sin i$ smaller than 0.08 km s$^{-1}$, a negligible contributor compared to the natural line width (thermal, turbulence) or instrumental. Instrumental broadenings are, at best, on the order of one to a few km s$^{-1}$ in the optical (e.g., PEPSI, ESPRESSO, respectively, with resolutions of up to 1.2 and 2.5 km s$^{-1}$; Mégevand et al. 2014; Strassmeier et al. 2015) or 3–4 km s$^{-1}$ in the near-infrared. It only shows a modest activity level with occasional flaring activity (Paulson et al. 2006) and its M4V spectral type corresponds to that of the bulk of nearby M dwarfs; furthermore, Barnard’s star spectral type is close to the median of that expected for TESS targets (Sullivan et al. 2015). Its surface gravity is expected to be slightly above $\log g = 5.0$ from evolutionary models (see Figure 1); this value is overall consistent with measurements of field M surface gravities (e.g., Ségransan et al. 2003). Metallicity ([Fe/H]) determination in the literature range from −0.13 to −0.52, for the comparison with the model we adopt [Fe/H] = −0.5. The properties of Barnard’s star are summarized in Table 1.

As one of our immediate galactic neighbors, this star has been subject to planet searches through astrometry (Benedict et al. 1998), direct imaging (Gauza et al. 2015), and RV (Kürster et al. 2003; Choi et al. 2013); but, to date no planet is known around this star, and HARPS measurements exclude the existence of planets with a mass superior to 5–6 $M_\oplus$ in its habitable zone (Bonfils et al. 2013).

3. Data Sets and Analysis

3.1. The HARPS Data Set

The HARPS high-resolution spectrum used is the median-combination of 22 individual spectra obtained during an RV planets search (Bonfils et al. 2013). HARPS (Pepe et al. 2000) is a fiber-fed spectrograph at the ESO/3.6-m telescope (La Silla, Chile). It covers the 380–680 nm wavelength domain with a resolution of $\lambda/\delta\lambda \sim 115,000$. We used 104 HARPS spectra from the ESO archive9 to build a high S/N (~850 per element) template of Barnard’s star. The individual spectra are reprocessed with the latest version of the standard HARPS pipeline (Lovis & Pepe 2007), using a nightly set of calibration exposures to locate the orders, flat-field the spectra (Tungsten lamp illumination), and precisely determine the wavelength-calibration scale (ThAr lamp exposure). To build the template, we shifted all de-blazed spectra to the rest frame and re-sampled them to a common reference wavelength. We then computed the median flux per spectral element, where the

| Spectral type | Rotation period | $v \sin i$ |
|---------------|-----------------|------------|
| M4 Ve$^a$     | ~130 days$^b$   | $\leq 80$ m s$^{-1}$ |

Notes.

$^a$ Kirkpatrick & McCarthy (1994).

$^b$ Benedict et al. (1998).

9 IDs 072.C-0488, 183.C-0437.
The raw frame was processed by CFHT QSO team using UPENA1.0, an in-house software that calls the LIBRE-ESPRIT pipeline Donati et al. (1997). LIBRE-ESPRIT performs optimal extraction of ESPaDOnS unpolarized (Stokes I) spectrum of the Star and the Sky fibers following the procedure described in Donati et al. (1997). In the present analysis, we used the processed subtracted (Star-Sky) spectrum with a normalized continuum. The accurate wavelength solution that accounts for instrument drifts was measured from strong telluric absorption lines. ESPaDOnS typically shows drifts well within a resolution element, with typical values below 300 m s\(^{-1}\). At the time of our observations, the measured drift was \(-104\) m s\(^{-1}\).

### 3.3. CRIRES-POP Spectra

CRIRES spectra were drawn from the CRIRES-POP\(^{10}\) spectral library (Lebzelter et al. 2012). Individual spectra from the library were analyzed separately, and we did not attempt to merge exposure into a single spectrum as we were interested in the shape of line profiles rather than the bulk SED properties. Each spectrum was drawn from the library and correlated against a telluric absorption spectrum. Slight offsets in the wavelength calibration (typically \(<5\) km s\(^{-1}\)) were corrected. We then extracted the time of observation from the file header and determined the barycentric correction for Barnard’s star. The CRIRES-POP data set has recently been used as a test data set for telluric line subtraction by modeling of absorption (Smette et al. 2015); while a similar approach could have been applied here to extract RV information from a larger spectral domain, we opted for the simpler approach of performing our analysis on nearly telluric absorption-free (<3%) parts of the optical and nIR.

### 3.4. Göttingen Spectral Library by Phoenix

For our analysis, we used PHOENIX-ACES models from the Göttingen spectral library\(^{11}\) (Husser et al. 2013); these are among the most up-to-date models available and are expected to better represent the nIR spectral features. More specifically, we used the data set labeled PHOENIX-ACES-AGSS-COND-2011-HiRes. The model grid is available with a 100 K temperature step and 0.5 dex \(\log g\) and metallicity steps. For the purpose of comparison with the model, we used a temperature of 3200 K, a sub-solar metallicity \((-0.5\) dex\) and \(\log g = 5.0\). Comparison with solar metallicity models (0.0 dex) and low-gravity models (\(\log g = 4.5\)) were also performed in order to assess the impact of varying these parameters on the RV content. The model wavelength grid is finer than the instrumental resolution, which is a necessary condition to properly re-sample models on the wavelength grid of the observations, with a sampling ranging from 0.3 to 0.6 km s\(^{-1}\). This is the same data set as used by Figueira et al. (2016), which leads to a better consistency between the two analyses.

In order to account for the finite resolution of instruments, before comparison with observations, models were convolved with the one-dimensional profile corresponding to that of a circular fiber. The adopted profile corresponds to the profile obtained by collapsing a two-dimensional circle image onto one axis. For a fiber-fed spectrograph, this corresponds to the profile of a monochromatic line in the approximation where the optical design image quality is significantly smaller than the diameter of the fiber. One can show that, arithmetically, this profile corresponds to a \(\sin\) function between 0 and \(\pi\). This profile is representative of most fiber-fed spectrographs (e.g., NIRPS, SPIRou, HARPS). As we are interested in differences between modeled and observed line profiles, we verified that our results were robust against a change in the assume instrumental line-spread-function. In addition to the collapsed-circle profile, we also performed all of the analysis presented here with a Gaussian profile having the same FWHM as the collapsed-circle one. All of the conclusions drawn here remain valid with a Gaussian profile.

### 3.5. Barnard and Field M4 Photometry

In order to derive an RV precision and compare the relative performance reached with various bandpasses, one needs to scale the flux with photometric measurement. We used the Mann et al. (2015) grizJHK values for Barnard’s star, but no \(Y\)-band measurement is available in the literature. We therefore used the mean \(Y - H\) color for M3.5–M5.5 dwarfs in Hillenbrand et al. (2002) \((Y - H = 1.07 \pm 0.07, \text{ or } Y = 5.87 \pm 0.07)\). This allows the scaling of \(N_e\) in Equation (1).

For all comparisons with \(z = 0\) metallicity models, we use the mean colors for M4V stars in Mann et al. (2015), excluding Barnard’s star; see numerical values in Table 2. These colors are used to scale models and estimate the S/N of a given bandpass relative to the \(J\) band. As expected for a low-metallicity object (e.g., Bonifils et al. 2005), Barnard’s star has slightly bluer optical to near-infrared colors than field stars; \(g - J\) and \(r - J\) colors being ~0.3 mag bluer. All colors with \(z, J, H,\) and \(K_s\) bands are within 0.1 mag of the field M4V. This is overall consistent with the results from Bonifils et al. (2005), Equation (1), where a 0.5 dex metallicity change corresponds to a 0.27 mag change in \(V - K\). While the strength of molecular bands has a significant impact on the RV content (see Section 4.3), the impact of color change is relatively modest, a difference of 0.3 mag corresponding to a \(~15\%)\) difference in S/N in the regime where observations are limited by the counting statistics from the source’s photons.

### 3.6. Telluric Absorption Spectrum

Most of the near-infrared domain suffers from absorption by the Earth’s atmosphere. Telluric absorption superimposes a set of sharp telluric lines on the stellar spectrum. As the line-of-sight

| color | Field | Barnard |
|-------|-------|---------|
| \(g - J\) | 5.42 | 5.13 |
| \(r - J\) | 3.91 | 3.62 |
| \(i - J\) | 2.34 | 2.21 |
| \(z - J\) | 1.48 | 1.44 |
| \(Y - J\) | 0.50 | 0.50 |
| \(J - H\) | 0.56 | 0.49 |
| \(H - K_s\) | 0.84 | 0.76 |

\(^{10}\) http://www.univie.ac.at/cirrespop/

\(^{11}\) http://phoenix.astro.physik.uni-goettingen.de
velocity of Barnard’s star changes through the year by \(\pm 32 \text{km s}^{-1}\), this component induces a time-varying signal that interferes with precise RV measurements. Telluric absorption represents a significant challenge to nIR pRV measurements and is discussed at length elsewhere (e.g., Bean et al. 2010; Seifahrt et al. 2010; Artigau et al. 2014a). Here, the main problem with telluric absorption in our data set is that its numerous lines add a significant contribution to the RV content of the spectrum of Barnard’s star. We used a model spectrum from the TAPAS\(^{12}\) (Bertaux et al. 2014) for the conditions prevailing at Paranal (airmass of 1, not convolved by an instrumental line width, observation date set as January 1). We included all molecular opacities proposed by the TAPAS interface (Rayleigh, H\(_2\)O, O\(_3\), O\(_2\), CO\(_2\), CH\(_4\), and N\(_2\)), with an ARLETTY atmospheric model corresponding to typical conditions occurring in Paranal. The sampling of the telluric absorption spectrum ranges from 0.2 to 1 km s\(^{-1}\), which is higher than the resolving power of any of our data sets and allows for an accurate interpolation onto the observed wavelength grid. We opted to compare only the RV content of both the observed and model spectra in domains where the atmospheric transmission is 97\% or greater. In order to assess the impact of having weak telluric absorption lines contaminating our stellar spectrum, we computed the model RV content with and without multiplying by the TAPAS telluric transmission model. The impact of weak (<3\% absorption) telluric lines affects the RV content of the stellar model at the 1\% level and is deemed negligible in the current analysis.

The exact amount of RV content that can be recovered in the presence of telluric absorption and its impact on the ultimate RV precision is a non-trivial problem (e.g., Section 3.7). Here, we are interested in comparing line profile and depth between models and observations, and not the impact of residual telluric absorption on high-precision velocimetry.

### 3.7. Useful RV Domain in the Presence of Telluric Absorption

Masking telluric lines from the stellar spectrum leads to the rejection of part of the wavelength domain that may otherwise be used for RV measurement, provided that efficient subtraction of the telluric absorption contribution can be performed. Various techniques have been proposed to do so: most using atmosphere models to fit telluric absorption (e.g., Guillikson et al. 2014; Smette et al. 2015), observing reference standard stars of B or A spectral type at roughly the same airmass as the observations (Vacc\(a\) et al. 2003) or empirical modeling without prior knowledge of telluric absorption (Artigau et al. 2014a).

Predicting an RV precision as derived from a model spectrum using a given observational setup in the presence of telluric absorption implies that we assume that telluric absorption will be subtracted up to a certain level. A very conservative approach would reject all of the domain that is affected by telluric absorption at any given time through the year. Such drastic wavelength domain rejection is definitely necessary when RV is computed in correlating the stellar spectrum to a reference that is not exactly similar (for example a cross-correlation of the stellar spectra with a numerical weighted mask). However, when the template is similar to the spectra of the star (e.g., median spectrum), only the wavelength domain under the telluric lines at the date of the measurement should be rejected. This is well demonstrated in the optical by Artigau et al. (2014a) in using RV computation presented in Astudillo-Defru et al. (2015) for an early M and a K dwarf.

Whether this holds in the near-infrared remains to be confirmed. As shown in Artigau et al. (2014a) for \(r\)-band HARPS observations of an M dwarf, domains with up to 10\% telluric absorption can be used for m s\(^{-1}\) RV measurements with a proper library of hot star observations. We therefore use this threshold for our RV precision predictions in Section 5, but the aforementioned caveats apply. To illustrate that our conclusions are only mildly dependent on the exact threshold used for telluric absorption masking, we also computed the RV precision for a much more conservative telluric absorption rejection threshold of <2\%. In order to compare the same wavelength domains, models were offset in RV to match that of Barnard’s star before masking telluric absorption and computing the RV content density \((Q);\) see Section 3.8).

### 3.8. Numerical Formalism

In the analysis, we follow the prescription of Bouchy et al. (2001). This work evaluates the ultimate precision to which a velocity shift can be determined in a well-sampled spectrum at high S/N. The RV precision is related to the quality factor \(Q\) through the relation

\[
\sigma_{\text{RV}} = \frac{c}{Q \sqrt{N_e}},
\]

where \(c\) is the velocity of light and \(N_e\) is the number of electrons collected per resolution element, assuming that observations are photon-noise limited (i.e., the effective readout noise per resolution element is much smaller than the photon noise, given by \(\sqrt{N_e}\)). As we are interested in comparing the RV precision predicted by models with that of observational data, only the \(Q\) value is relevant here as \(N_e\) is assumed to be the same. We therefore set

\[
\sigma_{\text{RV}} \propto \frac{1}{Q}.
\]

Following Bouchy et al. (2001) notation, \(Q\) is

\[
Q = \frac{\sqrt{\sum W(i)}}{\sqrt{\sum A_0(i)}}
\]

with

\[
W(i) = \frac{\lambda^2(i) \partial A_0(i) / \partial \lambda(i)^2}{A_0(i)};
\]

\(A_0(i)\) and \(\lambda(i)\) denote the flux at a given \((i)\) resolution element and the wavelength of that resolution element, respectively. \(Q\) is independent of flux and represents the density of RV content; conversion into an actual RV precision therefore only depends of the total flux \((N_e)\). Assuming that the underlying SED is similar within the bandpass of interest, one can therefore directly compare the ratio of \(Q\) values to assess the differences in RV content densities between models or observations and models. When comparing the RV precision that one can reach assuming an S/N within a given bandpass, one needs to properly scale the flux (i.e., the \(N_e\) term in Equation (1)) with actual photometric measurement from the target. As \(Q\) is a sum over a given wavelength domain and we are are considering in the spectral distribution of RV content, we will express \(Q\)

\(^{12}\)https://cds-espri.ipsl.upmc.fr/tapas/
integrated over short wavelength domains. The notation \( Q_{\Delta \lambda / \lambda} \) therefore indicates a sum of \( Q \) for a running \( \Delta \lambda / \lambda \) domain.

4. Results

4.1. Barnard’s Star RV Density Content

The RV content of Barnard’s star spectrum was measured from HARPS, ESPaDOnS, and CRIRES. The \( Q \) value is only computed for telluric-free regions as described in Section 3.6. The summation as expressed in Equation (3) is performed over \( \Delta \lambda / \lambda = 0.2\% \) domains through the optical and nIR domain; derived empirical and modeled values are showed in Figure 2. The \( Q \) values are globally consistent between models and observations in the optical (riz bandpasses). Near-infrared \( Q \) values are much more discrepant, with \( Y \)- and \( J \)-band values being over-estimated by models and \( H \) and \( K \) values underestimated. From these values, one can determine a median correction to be applied to models to predict the RV precision reachable in the photon-limited regime for all optical to near-infrared bandpasses. The correction corresponds to the flux-weighted mean ratio of \( Q_{\text{observed}} / Q_{\text{model}} \). A correction factor of 0.5 would correspond to an equivalent increase of a factor of 2 in RV error for a given S/N. The precision of the measurement worsens significantly, and this corresponds to a four-fold loss in observing efficiency (i.e., assuming that signal-to-noise increases as the square root of integration time). Correction values larger than one correspond to an improvement in precision; the RV precision expressed in m s\(^{-1}\) decreases.

Table 3 and Figure 3 provides the corresponding relative \( Q \) values.

Figure 2. (Top) Measured RV content of Barnard’s star over the optical and near-infrared domain. Overall measured (blue) and model (red) RV density are well matched blueward of \( \sim 1 \mu \text{m} \). The agreement is poorer in the near-infrared domain with an over-prediction of RV content in \( Y \) and \( J \) bands and an under-prediction in \( H \) and \( K \). (Bottom) Ratio of observed to model \( Q_{0.2\%} \) values. Areas unusable for RV measurements because of strong telluric absorption are filled in light blue.
factors \( Q_{\text{observed}}/Q_{\text{model}} \) correction for grizYJHK bandpasses as well as the values derived for different stellar models.

### 4.2. Correction Value Dependence on Model Choice

The exact physical parameters of Barnard’s star (metallicity, effective temperature, surface gravity) have been measured by several groups and modest discrepancies exist in the literature (see Table 1). It is therefore important to assess whether the results described here hold for different choices of model parameters. The previous results, i.e., that the RV content is over-estimated in \( Y \) and \( J \) and is under-estimated in \( H \) and \( K \), remains true if one of the above parameters is changed to one of the extremes of the plausible physical range. Table 3 and Figure 3 compile the correction factor that needs to be applied on the RV precision at a given S/N for grizYJHK bandpasses as derived from our data set. The nominal correction applies to a \( \log g = 5.0, -0.5 \) dex metallicity and \( T_{\text{eff}} = 3200 \) K, and corresponds to the nominal model values shown in Figure 3. The values derived when using slightly different models differ, but the overall conclusions remain valid. As shown in Figure 4, models at solar metallicity have a higher \( Q \) value in the \( H \) and \( K \) bands, leading to a more modest correction than for sub-solar metallicity at the same \( T_{\text{eff}} \).

Figure 3. Correction factors \( (Q_{\text{observed}}/Q_{\text{model}}) \) for the RV precision. The various models tested are described in Section 4.2.

Table 3

| [Fe/H] | \( \log g \) | \( T_{\text{eff}} \) (K) |
|--------|-------------|------------------|
| -0.5   | 5.0         | 3200             |
| 0.0    | 5.5         | 3400             |
|        | 5.5         | 3000             |

Note. These values correspond to the square root of the flux-weighted mean \( Q \) ratio between observation and models for each bandpass. The nominal values are for a comparison with the default model described here, but we also explore the impact of other physical parameter choices.

Figure 4. Density of RV content for the optical and near-infrared domain. The top panel shows the RV density \( Q_{5\%} \) for three models: the nominal Barnard’s star model (red), the field mid-M at solar metallicity (green), and a low-surface gravity, young, M dwarf (blue). All three models are normalized to the \( Q_{5\%} \) value of the “Barnard’s star” model in \( J \). The \( i \) band (\( \sim 0.7 \) \( \mu m \)) contains the highest RV density content, which favors instruments observing in the far-red (see Section 5). Solar-metallicity M dwarfs are expected to have a higher RV content than Barnard’s star in the near-infrared. The bottom panel shows in red the \( Q \) density for the “Barnard’s star” and in blue the “Young” models normalized to the “Field” model.

4.3. Qualitative Assessment of RV Content Differences

The results we detailed in Section 4.1 show a significant difference between predicted and observed RV content for Barnard’s star in YJHK bands. The difference should lead to notable differences in a direct visual comparison of observed and model spectrum. Figure 5 represents two regions of the
J and H bands, chosen due to the abundance of sharp lines. The over-estimation in the J band can be traced to deeper and sharper predicted lines than observed. As mentioned earlier, the RV content is proportional to the power $3^2$ of the full-width at half maximum (FWHM) of lines, so modest differences in line shape leads to significant differences in the predicted RV precision. In H band, numerous lines are observed but not predicted, which is most-likely due to incomplete line lists, as suggested by Figueira et al. (2016). It is noteworthy that the RV content is better determined in the optical and far-red, a wavelength domain that has historically received more attention. Lines are blended at all wavelengths for M dwarfs and one cannot directly measure an effective line shape directly with isolated lines as can be done for earlier-type stars. We therefore determined the auto-correlation of the spectrum for telluric-free parts of grizJHK bands. The auto-correlation profile of the stellar spectrum is directly linked to the mean line profile, both instrumentally and physically. From the auto-correlation profile, we recovered the effective mean line profiles (see Figure 6) for both observed and model spectra. In J and H, the full-width at half maximum of the line profile is $\sim 5 \, \text{km s}^{-1}$, while models predict significantly narrower lines in J. This is consistent with the results displayed in Figure 5, where numerous lines are deeper and narrower in models than they are in the observed spectrum, thus leading to an over-estimation of the RV content in J. In the optical domain and K band, the agreement between the observed and model profiles is remarkable. The only notable difference between models and observations are the broader line wings in the i and z bands.

5. Discussion

The results presented here allow one to empirically correct RV content predictions from models. The extent of the validity of these correction factors, both in effective temperature and surface gravity, remains to be established with an analysis comparable to the one presented here, but spanning a range of spectral types. If we assume that the $Q_{\text{observed}}/Q_{\text{model}}$ ratios measured for Barnard’s star hold at a solar metallicity, one can predict the RV precision that will be achievable for mid-Ms observed by upcoming nIR RV spectrographs.

We assume that a bandpass contribution to the RV budget scales as $s_{\text{RV}}^2$. Two bandpasses that provide a $s_{\text{RV}} = 1.4 \, \text{m s}^{-1}$ contribute as much as a single band for which a $s_{\text{RV}} = 1 \, \text{m s}^{-1}$ measurement is possible in the same amount of time. Figure 7 shows the RV precision per bandpass that is reached for a $T_{\text{eff}} = 3200 \, \text{K}$ model in three metallicity and surface gravity conditions.
scenarios. The relative contribution of $Y$ and $J$ to the near-infrared RV content budget is predicted to be much smaller than models suggest. For an instrument covering $YJH$ at $R \sim 100,000$ (e.g., NIRPS), it is predicted that $Y$, $J$, and $H$ contribute 39%, 42%, and 19% of the RV budget, respectively. After correction and at solar metallicity, the relative fraction is 7%, 14%, and 79%. Table 4 provides the RV accuracy achievable, per bandpass, accounting for both flux differences between bands and differences in RV content, all other things being equal. A solar metallicity will lead to slightly improved RV accuracy for all bandpasses other than $Y$ and $J$. In all cases, the $i$ band provides the most accurate measurement.

For an instrument covering the $YJHK$ domain (e.g., SPIRou, GIANO), the relative contribution of $Y$ and $J$ is even smaller. Models suggest a similar contributions from all bandpasses (30%, 31%, 20%, 18%) but the correction derived here leads to a much larger relative contribution longward of 1.5 µm (3%, 6%, 45%, 47%) for solar metallicity. Overall, $H$ and $K$ move from a 38% to a 94% contribution to the RV budget.

The importance of the $H$ and $K$ bands relative to $Y$ and $J$ implies that an RV spectrograph that observes within a single photometric bandpass at a time such as CRIRES+ will be nearly as efficient in $H$ as a similar instrument that would cover the entire $YJH$ domain. The inclusion of $K$ in an instrument such as SPIRou nearly leads to a doubling of the RV content. These results cast a doubt on the conclusion by Rodler et al. (2011) that concludes that for M9 and L dwarfs, the most important contribution the the RV content came respectively from $Y$ and $J$. Admittedly our measurement of the RV content of Barnard’s star concerns an object $\sim1000$ K hotter, but if the missing opacities in $H$ and $K$ are also present in very-late-Ms and Ls, then these results will need to be revisited. Our results also underline the limitations of works such as Reiners et al. (2010) and Figueira et al. (2016), who, being based on stellar models very similar to the ones presented here, were affected by important systematic errors in the RV estimates.

Having derived correction values for all photometric bandpasses, we can predict the performance for different spectrographs’ resolution and nIR domain coverage. We explore the various scenarios corresponding to existing and under development PRV spectrographs. Table 5 provides the RV precision reached for a common set of assumptions regarding the target star. As for the above calculation, we assume a mean $S/N$ of 100 per $\Delta \lambda = 3$ km s$^{-1}$ at the center of the $J$ band. We did not attempt to provide an exhaustive comparison of the performances of RV spectrographs, an effort that would be far beyond the scope of the current paper. PRV spectrographs are installed on telescopes of differing diameters, their overall throughput and intrinsic stability differ, and the performances of recently commissioned instruments is likely to improve in the future. Furthermore, depending on the wavelength domain probed, the sensitivity to stellar activity will differ; infrared spectrographs being advantageous, for that matter, relative to optical and far-red PRV instruments (e.g., Barnes et al. 2011). Our comparison therefore only applies to the photon-noise contribution in the complete RV error budget, at a common flux level.

We confirm earlier results (e.g., Reiners et al. 2010, Seifahrt et al. 2016) that spectrographs covering the far-red ($griz$ bands) outperform an instrument covering the $YJHK$ domain at the same spectral resolution. In the far-red, the higher RV content

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**Table 4**

Radial Velocity Achievable for a $T_{\text{eff}} = 3200$ K M Dwarf Assuming a Median $S/N = 100$ in $J$, for a $\lambda/\Delta \lambda = 10^5$ Resolution Element, Derived from Models with $\log g = 5.0$ and $-0.5$ dex Metallicity (Barnard) and, $\log g = 5.0$ and 0.0 dex Metallicity (Solar)

| Band | Absorption < 10% |  | Absorption < 2% |  |
|------|----------------|---|----------------|---|
|      | Barnard Model (m s$^{-1}$) | Corr. (m s$^{-1}$) | Solar Model (m s$^{-1}$) | Corr. (m s$^{-1}$) |
|      | g | 2.84 | 4.30 | 2.71 | 4.11 |
|      | r | 2.78 | 3.41 | 2.58 | 3.16 |
|      | i | 1.73 | 1.84 | 1.49 | 1.59 |
|      | z | 3.31 | 2.60 | 2.84 | 2.23 |
|      | Y | 3.49 | 11.90 | 3.56 | 12.15 |
|      | J | 3.35 | 8.72 | 3.52 | 9.15 |
|      | H | 4.99 | 3.64 | 3.45 | 2.51 |
|      | K | 5.34 | 3.63 | 3.86 | 2.63 |
|      | Barnard Model (m s$^{-1}$) | Corr. (m s$^{-1}$) | Solar Model (m s$^{-1}$) | Corr. (m s$^{-1}$) |
|      | g | 2.84 | 4.30 | 2.71 | 4.11 |
|      | r | 2.79 | 3.41 | 2.58 | 3.16 |
|      | i | 1.74 | 1.85 | 1.51 | 1.60 |
|      | z | 3.27 | 2.57 | 2.75 | 2.16 |
|      | Y | 3.47 | 11.84 | 3.55 | 12.11 |
|      | J | 3.27 | 8.51 | 3.45 | 8.96 |
|      | H | 5.14 | 3.75 | 3.54 | 2.58 |
|      | K | 6.29 | 4.28 | 4.51 | 3.07 |

Note. The corrected values derived from data set detailed here are given. Values have been computed for the domain within each bandpass with a telluric absorption <10% (nominal) and <2% (conservative).
density compensates for the lower flux. Interestingly, in such a spectrograph, the i band is more important than z despite the red i − z color of M dwarfs. Qualitatively, this can be seen in Figure 2, where the i band has a higher Q value than z. Reiners et al. (2017) present an analysis of 324 M dwarf spectra in order to assess their RV content and wavelength dependency. There are notable differences between the present analysis of Barnard’s star spectrum and that of the representative mid-M shown (e.g., Figure 7 therein and, in particular, the M3.5 Luytens star). In our analysis, the relative contribution of the J and H bands differs significantly while in Reiners et al. (2017), the two bands lead to comparable RV accuracies. Similarly to our results, Figueira et al. (2016) predicted a precision much worse for J than for H; for the M3 model, λ/Δλ = 80000, v sin i = 1 and for optimal telluric subtraction, the RV accuracy predicted varies from 5 m s$^{-1}$ in H and 16.5 m s$^{-1}$ in J (see Table A.1 therein). As pointed out in Reiners et al. (2017), residual telluric absorption may lead to an increased RV content in their data set. Residual telluric absorption is also suggested as an explanation for the mismatch between the RV-content-based prediction of the RV uncertainties and the measured values.

The lack of M dwarf spectral libraries covering the entire near-infrared at high resolution until very recently incited previous authors to use models to predict RV content, which, in itself, adds some uncertainties in the interpretation of results. The recent publication of a sample of spectra obtained with CARMENES (Reiners et al. 2017) partially fills this gap. A need nonetheless remains for a near-infrared spectral atlas cleaned form telluric absorption, either through modeling and/or a combination of multiple observations obtained at sufficiently different barycentric velocities.

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