Leibniz-Institut für Astrophysik Potsdam

AIP

VATICAN OBSERVATORY

LARGE BINOCULAR TELESCOPE

PEPSI

The Potsdam Echelle Polarimetric and Spectroscopic Instrument

PEPSI deep-spectrum library

Gaia benchmark stars and other M-K standards

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We provide a homogeneous library of high-resolution, high-S/N spectra for 48 bright AFGKM stars, some of them approaching the quality of solar-flux spectra. Our sample includes the northern Gaia benchmark stars, some solar analogs, and some other bright Morgan-Keenan (M-K) spectral standards. Well-exposed deep spectra are created by average-combining individual exposures. Our data-reduction process relies on adaptive selection of parameters by using statistical inference and robust estimators (see poster by I. Ilyin). We employ spectrum synthesis techniques and statistics tools in order to characterize the spectra and give a first quick look at some of the science cases possible.

With an average spectral resolution of R ≈ 220, 000 (1.36 kms−1), a continuous wavelength coverage from 383 nm to 912 nm, and S/N ratios between 100:1 for the faintest stars in the extreme blue and 4,000:1 for the brightest stars in the red, these spectra are made public for further data mining and analysis. Preliminary results include new stellar parameters for 70 Vir and α Tau, the detection of the rare-earth element dysprosium and the heavy elements thorium and neodymium in several RGB stars, and the use of the 12C/ 13C isotope ratio. We also found Arcturus to exhibit tiny Ca II H&K and Hα residual profile changes with respect to the KPNO-atlas spectrum taken in 1999.

Table 1. Stellar sample of deep PEPSI spectra.

Star	M-K class	Combined S/N ratio[a] I/404	II/450	III/508	IV/584	V/685	VI/825	*N* spectra[b]
Giants								
32 Gem	A9 III	120	260	350	470	480	420	222 222
HD 140283	F3 IV		200	300	460	480	660	222 224
HD 122563	F8 IV		240	400	770	740	750	222 224
η Boo	G0 IV							233 36(10)
ζ Her	G0 IV							286 56(14)
δ CrB	G3.5 III	320						122 223
μ Her	G5 IV							28(13) 8(10)(13)
β Boo	G8 III							3(10)(10) (10)(10)(14)
ϵ Vir	G8 III		130	220	450	730	1970	363 33(11)
β Gem	K0 IIIb							693 83(11)
HD 107328	K0 IIIb		430	630	1110	1240	1700	343 436
α UMa	K0 III		180	290	640	900	1600	363 339
α Ari	K1 IIIb	680	530	640	1630	1250	1400	366 866
α Boo	K1.5 III	540	1100	520	1200	3900	3200	6(14)4 7(46)(17)
7 Psc	K2 III							233 334
μ Leo	K2 III	260	430	750	940	1400	1850	234 34(16)
γ Aql	K3 II							2(11)5 56(11)
β UMi	K4 III		270	510	760	1100	2100	433 33(12)
α Tau	K5 III							3(11)8 (12)8(10)
μ UMa	M0 III							396 76(15)
γ Sge	M0 III							2(13)9 9(10)(17)
α Cet	M1.5 IIIa							326 962
Dwarfs								
α CMa	A1 V	800	590	720	740	620	420	111 111
HD 84937	F2 V		90	180	170	260	100	352 523
σ Boo	F4 V							4(10)5 45(18)
HD 49933	F5 V-IV							126 262
α CMi	F5 V-IV		430	610	1040	1550	1660	5(12)6 66(14)
θ UMa	F7 V							4(14)8 88(20)
β Vir	F9 V		90	150	330	440	1240	273 43(10)
HD 22879	F9 V		290	260	540	380		121 211
HD 189333	F9 V							111 111
HD 159222	G1 V							232 323
16 Cyg A	G1.5 V		250	400	530	650	600	122 223
HD 101364	G2 V		180	300	350	470	410	336 363
HD 82943	G2 V		180	260	340	390	330	322 223
18 Sco	G2 V		310	590	1040	1300	850	433 773
51 Peg	G2.5 V							344 445
16 Cyg B	G3 V		340	430	700	1110	810	222 263
70 Vir	G4 V	250	450	700	910	1160	1340	222 224
μ Cas	G5 V							122 222
HD 103095	G8 V		270	450	670	700	750	233 433
τ Cet	G8.5 V							566 896
ϵ Eri	K2 V							156 565
HD 192263	K2 V							122 222
HD 128311	K3 V		115	190	290	350	430	322 223
HD 82106	K3 V		75	250	240	480	360	213 132
61 Cyg A	K5 V							124 354
61 Cyg B	K7 V							122 224

Data product:

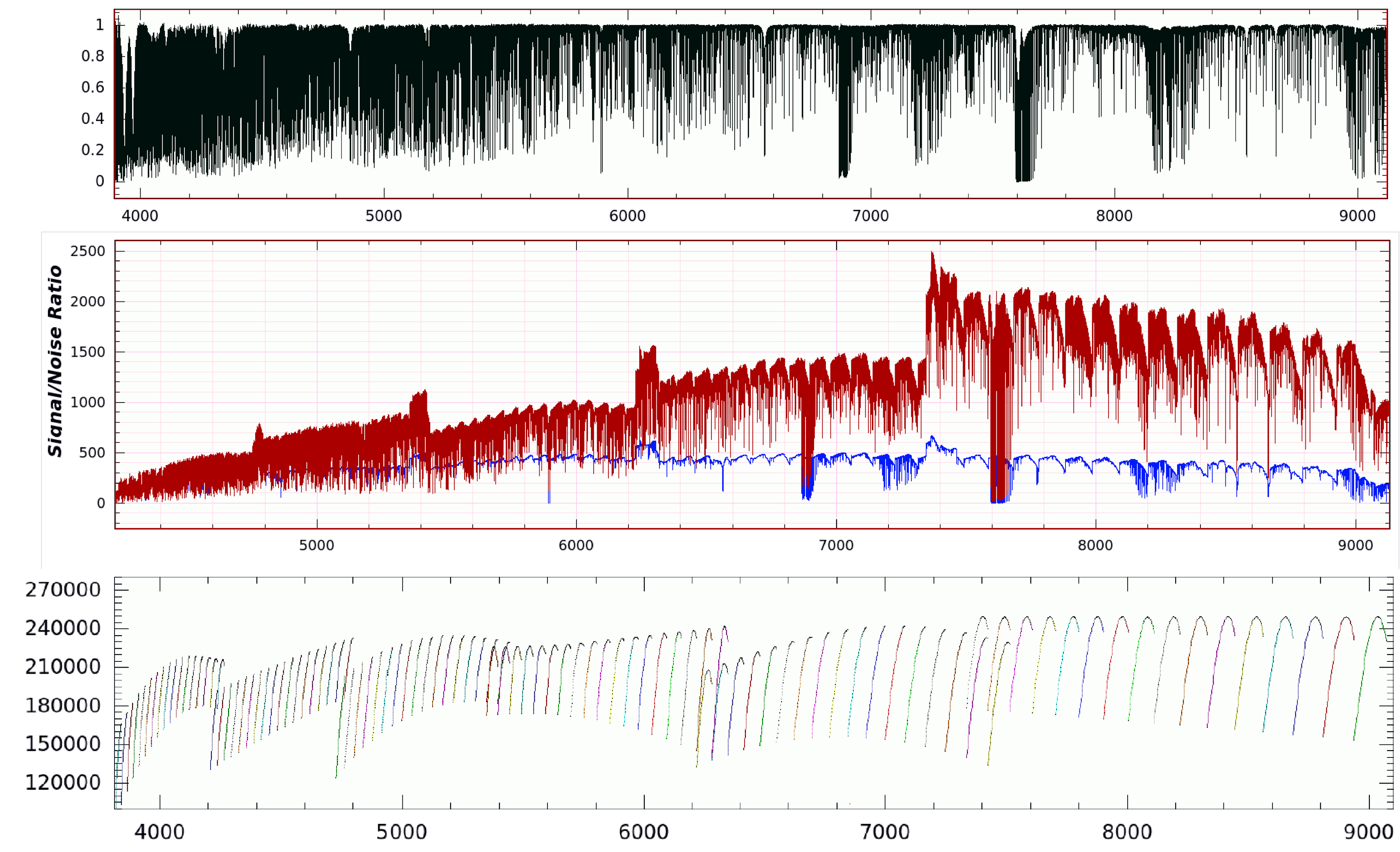

Fig. 3. Examples for the typical S/N ratios and spectral resolution of the library stars in this paper. *a.* Shown is the S/N ratio of the deep spectrum of the G4V-star 70 Vir. The larger S/N in the very red wavelengths is mostly due to the larger number of individual spectra. Note that the local peaks in S/N ratio are due to the wavelength overlap of the cross dispersers, which effectively doubles the number of pixels there. *b.* Shown is the spectral resolution for the focus achieved for the July 2016 run.

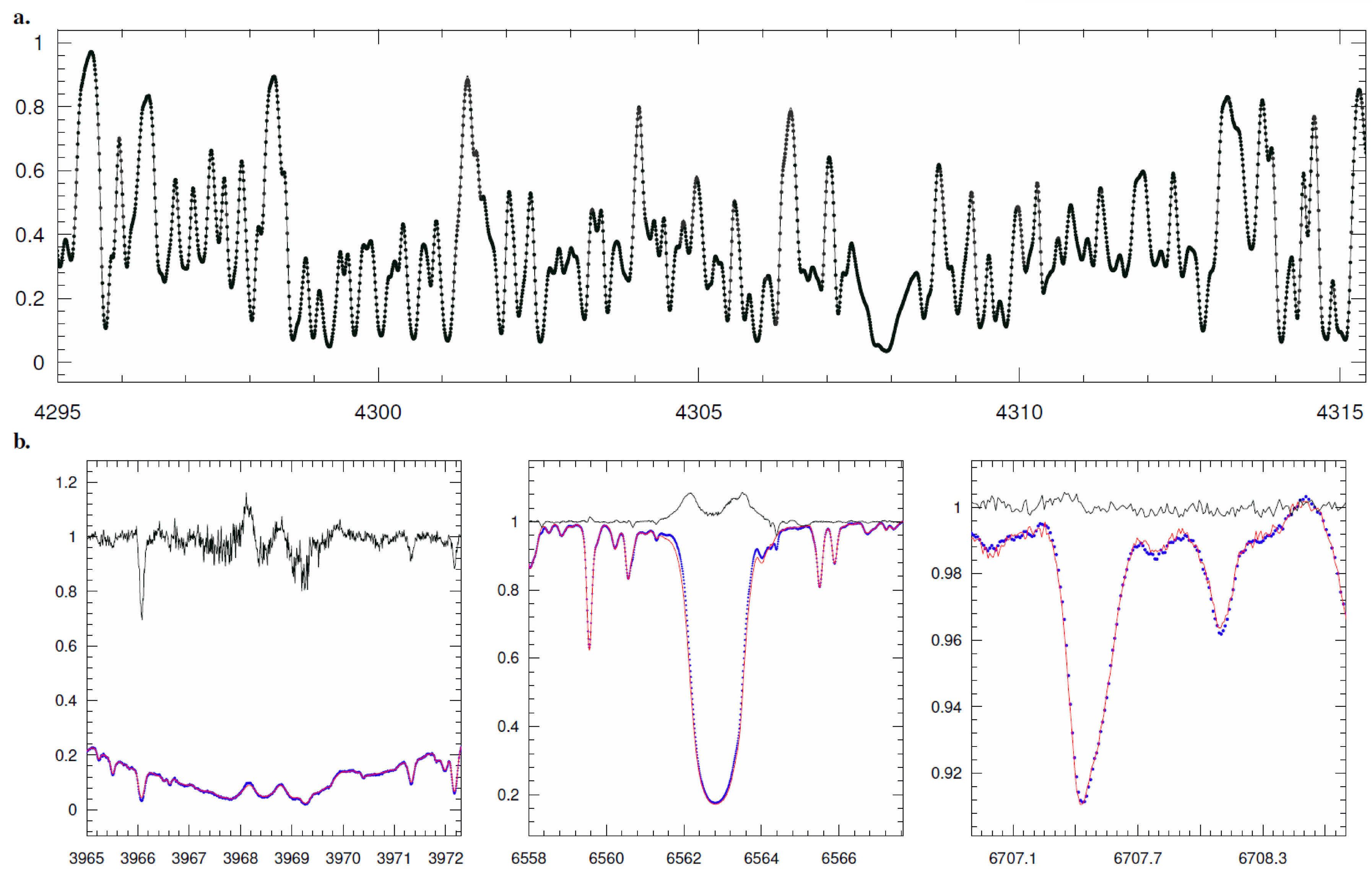

Fig. 4. A comparison of the deep PEPSI spectrum of Arcturus with the KPNO Arcturus atlas from Hinkle et al. (2000). *a.* Shown are the numerous CH lines centered around the Fe I/Ca I blend at 4308 Å that constitute the Fraunhofer *G*-band. The dots are the PEPSI spectrum and the line is the KPNO atlas. The match is nearly perfect. *b.* Three wavelength regions where chromospheric activity may be detected. Each panel shows the ratio spectrum PEPSI:KPNO (line around unity), the KPNO spectrum (line), and the PEPSI spectrum (dots). From left to right, the core of the Ca II H line, Hα, and the Li I 6708-Å doublet.

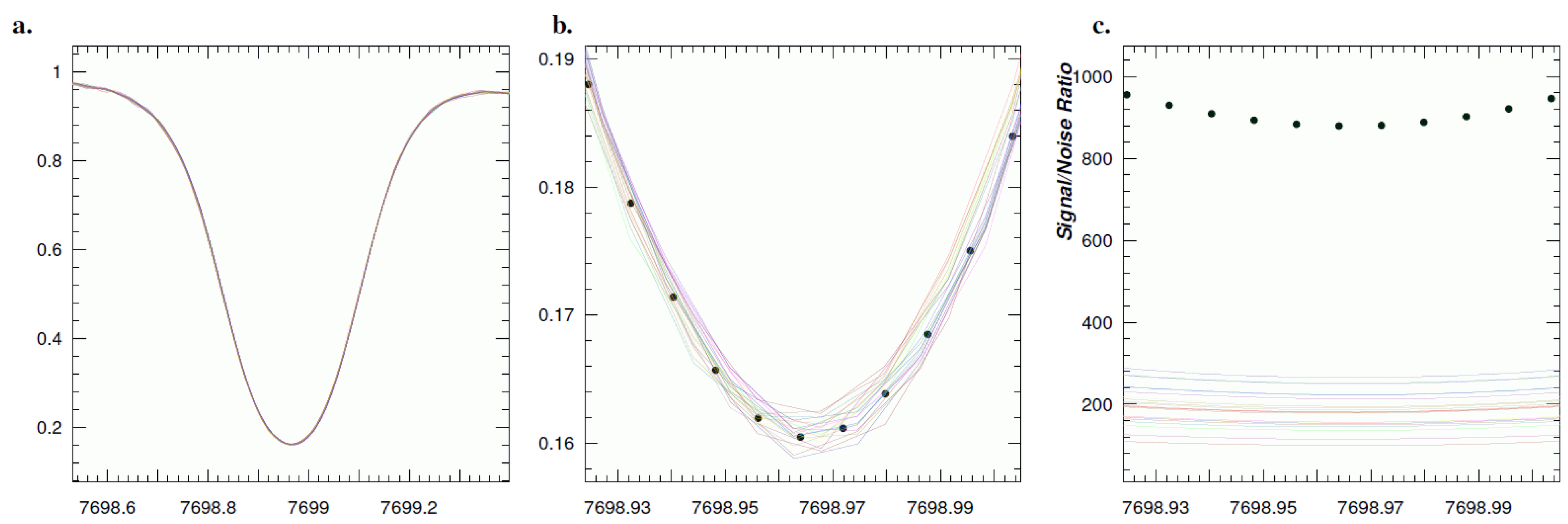

Fig. 2. A comparison of an average-combined spectrum and its individual exposures for β UMi (K4III). The 22 individual exposures are shown as lines, the average combined "deep spectrum" as dots. *a.* An 0.8-Å section showing the 22 exposures of the K I 7699 Å line profile. No differences can be seen at this plot scale. *b.* A zoom into an 0.08-Å subsection of the line core. The spacing of the dots represent the CCD pixel dispersion. *c.* S/N ratio per pixel in the K I line core for the same spectral window as in panel *b.*.

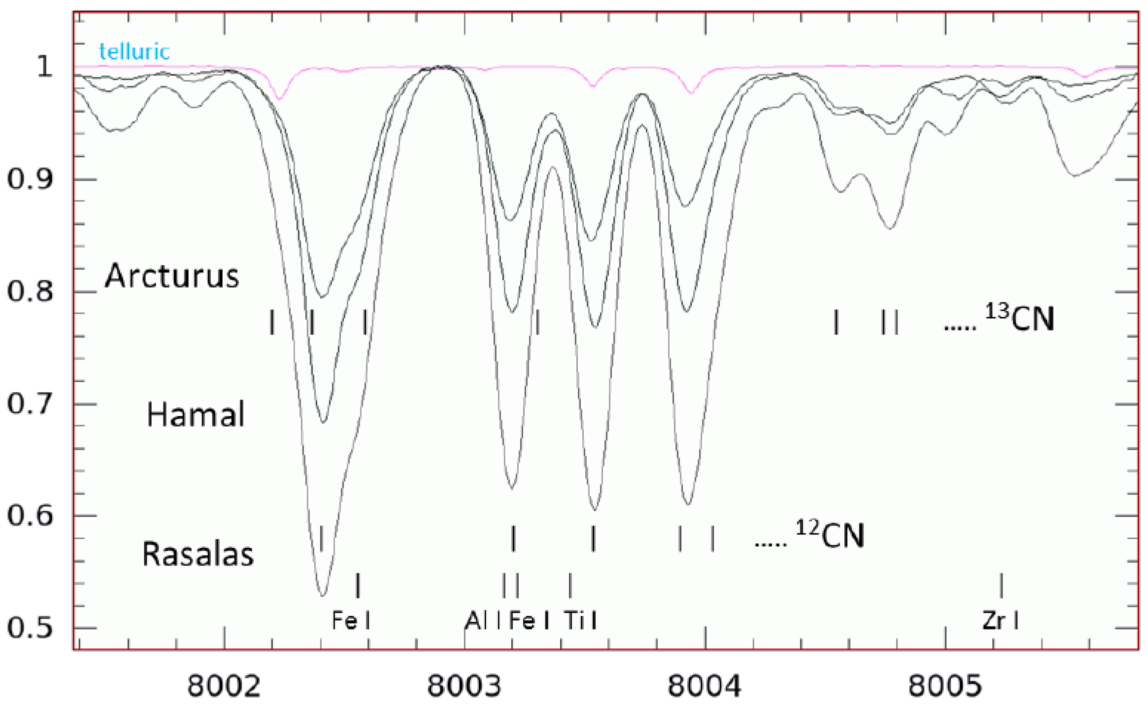

Fig. 6. A comparison of the 800-nm region of three RGB stars in this library; from top to bottom, Arcturus (α Boo, K1.5III), Hamal (α Ari, K1IIIb), Rasalas (μ Leo, K2III). The region contains many ^{12}CN and ^{13}CN lines from which the ^{12}C/^{13}C ratio is derived. A telluric spectrum scaled to the Rasalas observation is shown on the top.

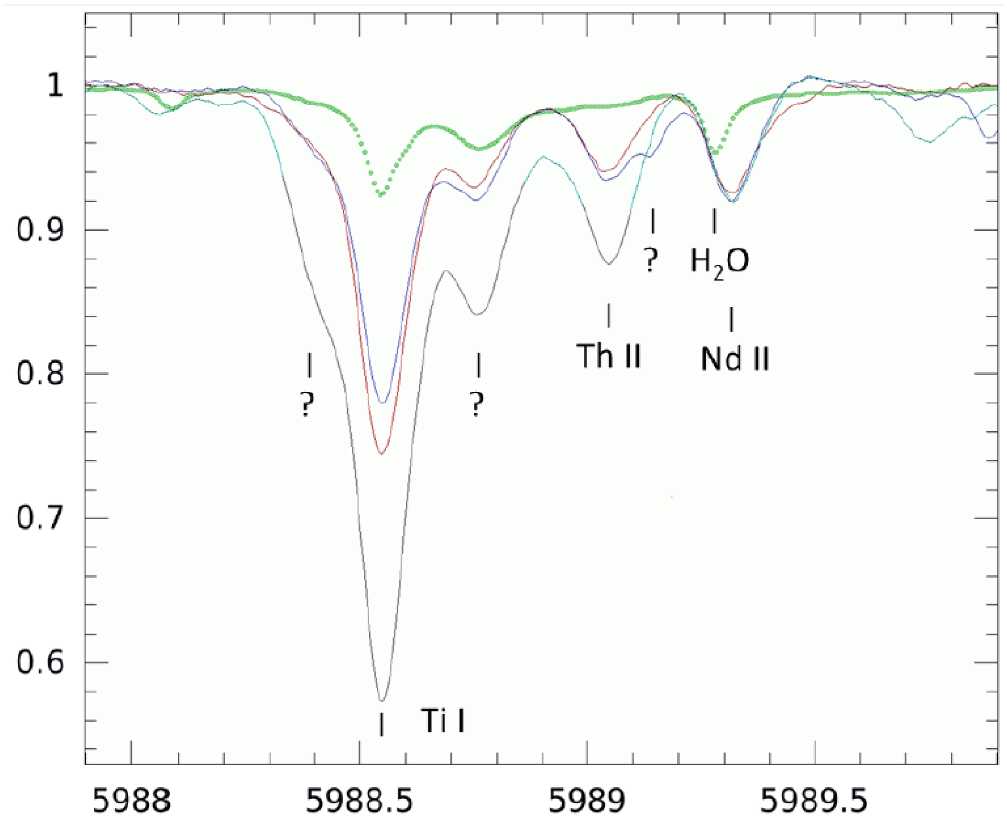

Fig. 7. Th II 5989.045-Å and Nd II 5989.378-Å lines in three RGB stars (full lines, identifications as in Fig. 6) compared to a spectrum of the Sun (dots).

We touched on several archival science cases possible to be followed up with the present data. Among these are the determination of global stellar parameters like effective temperature, gravity, metallicity, and elemental abundances. For a demonstration, we applied our spectrum synthesis code ParSES to a number of selected PEPSI wavelength regions of 70-Vir (G4V) and α Tau (K5III). The resulting values are summarized and compared with the literature. These numbers are not intended to be the final verdict but shall just demonstrate the capabilities and the expected uncertainties.

Of particular interest are isotopic line ratios. The most asked for in the literature is the 6Li/7Li ratio from the two Li doublets at 6708Å . Its science cases range from rocky planet engulfment, internal stellar mixing and dredge-up mechanisms, to the primordial Li production rate. In our paper I on the Sun-as-a-star, we had analyzed this wavelength region of the Sun in detail and refer to this paper (poster). Another isotope ratio of general interest is 12C/13C. Its primary science case is the main chain of the CNO cycle in stellar evolution but also allows the quantification of dredge-up episodes on the RGB in more detail. Finally, elemental abundances of species "that are hard to get at" are made accessible, e.g., the rare-earth element dysprosium or the heavy elements uranium and thorium, just to name a few.

After acceptance by A&A, the reduced deep spectra can be downloaded in FITS format from our web page at

https://pepsi.aip.de

Condensed view of the library spectrum of the solar twin 18 Sco (bottom left corner 382nm, top right corner 912nm).