High-Resolution Near-Infrared Spectroscopy of Hot Supergiants

A. W. Fullerton[1, 2] and F. Najarro[1]

Universitäts Sternwarte München, Scheinerstraße 1, D–81679 München, Germany

Abstract. We present the results of a pilot project to obtain high-resolution (∼10 000), high-S/N (∼100) J-, H-, and K-band spectra of a selection of hot, luminous supergiants with the Fourier-transform spectrometer of the Canada-France-Hawaii Telescope. The spectra are illustrated in a series of montages and preliminary results of detailed modelling of the hot hypergiant HDE 316285 are presented.

1. Introduction

Infrared (IR) spectroscopy in the J, H, and K bands has many useful applications to studies of hot stars. At modest resolutions (500–1000), the classical techniques of spectral classification can be used to assess the hot stellar content of dusty environments like young H II regions, from which little or no light penetrates at optical wavelengths; see, e.g., the contributions by Conti and Hanson to these proceedings. With higher resolution (∼1000–3000), quantitative analysis of individual spectral features provides considerable diagnostic leverage for mass-loss studies, particularly for targets in obscured regions like the Galactic centre; see, e.g., the work reported by Najarro and Crowther in these proceedings. For some applications (e.g., detailed mapping of the velocity field of the stellar wind) even higher resolution (∼10 000–20 000) is desirable, but cannot be delivered by the present generation of IR grating spectrographs. This situation is expected to improve dramatically in the next few years, owing to rapid advances in IR detector technology.

However, it has in fact been possible to obtain high-S/N, high-resolution near-IR spectra of bright targets for many year by using interferometric instruments, in particular the Fourier-transform spectrometer (FTS). A modern FTS is a highly refined version of the classical two-armed Michelson interferometer (see, e.g., Schnopper & Thompson 1974; Ridgway & Brault 1984), and as such it presents some distinct advantages over traditional grating spectrographs for IR spectroscopy of bright objects:

---

[1] Visiting Astronomer, Canada-France-Hawaii Telescope, operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique de France, and the University of Hawaii.

[2] Current address: Dept. of Physics and Astronomy, The Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218, USA.

- Spectral resolution: for conventional grating spectrographs, the resolution of the final spectrum is determined by a variety of factors, e.g., the density of rulings on the grating, the order of diffraction, the width of the entrance slit, the focal length of the spectrograph camera, and the pixel size of the detector. In contrast, the resolution of an FTS scan depends on the total path difference between the two arms of the interferometer. This can be selected at the time of observation, and can vary from modest values to a maximum (typically $\sim 10^6$) set by the total range of travel of the moving mirror (which is usually on the order of 500 cm or more).

- Spectral coverage: the wavelength coverage of an FTS is determined by the filters inserted into the light beam and can be very much larger than the coverage available to grating spectrographs (with the possible exception of echelle spectrographs). For example, the entire J, H, and K bands can be observed in one scan.

- Sky subtraction and noise suppression: with modern dual-beam designs, sky subtraction occurs automatically. Scintillation noise (which is a problem because the single-channel detector is illuminated by the flux from a large waveband) and noise due to dome vibration can be minimized in the observed signal by modulating the position of the moving mirror at frequencies of 100–300 Hz. These low-amplitude, rapid modulations effectively shift the data to higher-frequency bands, where the effects of scintillation and dome vibration are small.

These advantages are offset primarily by the limited sensitivity typical of interferometers (see, e.g., Ridgway & Hinkle 1992), the comparative complexity of observing with them, and the fact that the instrumental function, although well determined and controllable, is 'delocalized' through the resultant spectrum. The reduction of FTS spectra also poses some challenges; however, these are not substantially different from the reduction of data obtained with other modern instruments.

In this paper we describe a pilot study to determine the feasibility of using the FTS of the Canada-France-Hawaii Telescope (CFHT) to obtain obtain high-resolution ($\sim$10 000), high-S/N ($\sim$100) J-, H-, and K-band spectra of hot stars for quantitative analysis. This instrument, which was built by Dr. J.-P. Maillard and commissioned in the early 1980s, has been called the "last word" in astronomical FTS (Johnston 1991); see Maillard & Michel (1982) for a complete description of its properties.

2. Observations and Reductions

During a three-night run at CFHT in 1995 August, we obtained infrared spectra with resolutions of 8200–10 000 and S/N of 50–100 for a small sample of objects, which included the extreme P-Cygni star HDE 316285, the luminous blue variable (LBV) HD 160529, and an assortment of other bright supergiants with spectral types distributed between B1.5 and A3. Table 1 records some basic properties of these objects, which were obtained from the Bright Star Catalogue (Hoffleit & Jaschek 1982) or the SIMBAD database. Unfortunately, we did not

Table 1. Targets for CFHT/FTS Pilot Study.

HD/HDE	Other	SpT [a]	V	$(B-V)$	J	H	K
316285		B0 Ia$^+$	9.11	+1.67	4.90	4.10	3.60
190603		B1.5 Iae	5.64	+0.54	4.50	4.14	4.03
36371	χ Aur	B5 Iab	4.76	+0.34	...	...	3.75
34085	β Ori	B8 Ia	0.12	−0.03	...	...	0.09
197345	α Cyg	A2 Ia	1.25	+0.09	1.00	0.90	0.89
160529	V905 Sco	A3 Iae [b]	6.67	+1.28	3.55	3.14	2.84
223385	6 Cas	A3 Iae	5.43	+0.67	...	...	3.40

[a] Spectral Type.
[b] LBV with recent spectral type B8–B9 (Sterken et al. 1991).

acquire spectra in each filter for all the targets: specifically, we did not obtain J- and K-band spectra of HD 223385, nor H-band spectra of HD 36371 and HD 160529. In the case of HDE 316285, we used a narrow filter centred on He I 1.083μm in place of the full J-band filter.

An observational sequence in a particular filter consisted of multiple pairs of 'forward' and 'reverse' scans of the movable mirror, starting from zero path difference and extending to the path difference required to obtain the desired spectral resolution. The step size over this range was determined by the need to avoid aliasing when the spectrum (i.e., the Fourier transform of the interferogram) was computed; thus, by virtue of the sampling theorem, the step size was inversely proportional to the range of wavelengths covered by the filter. In the case of K-band observations of HD 190603 (the faintest of our targets in the K band) there were 4096 steps per scan, each of which received an integration of 150 msec; consequently, a single scan required $\sim$614 seconds (10.2 minutes) to complete. Four scans were obtained (2 in the 'forward' direction and 2 in the 'reverse' direction), to ensure that the S/N in the final coadded spectrum would be $\sim$100. These required a total overhead of 9 minutes to balance the arms of the interferometer at the start of the forward/reverse scan sequences. Thus, 50 minutes were required to obtain a high-S/N, high-resolution spectrum of the entire K band for a fourth-magnitude star (in the K band), of which 41 minutes were 'on source'.

Most of the subsequent processing of the interferograms was accomplished by means of the 'standard' reduction package written by J.-P. Maillard. This involved establishing the point of 'zero path difference' very accurately from the data themselves, reconstructing the interferogram accordingly, computing its Fourier transform to create a spectrum, and coadding the spectra from successive scans of a particular filter. The filter function, which is usually quite complicated, was removed from the stellar spectrum by division of a high-quality lunar spectrum that had been obtained at a similar airmass. This also removed most of the telluric lines from the stellar spectra (except in places where the telluric contamination was extremely strong), but had the unfortunate consequence of imprinting the solar spectrum on the stellar data. We manipulated machine-readable versions of the high-resolution solar atlases of Livingston & Wallace (1991) and Wallace, Hinkle & Livingston (1993) to remove the unwanted solar signal from the stellar spectra. This final step involved degrading the resolution of the solar spectrum to match the resolution of the CFHT FTS and accounting for small residual differences in line strength and position. The degree to which the solar spectrum can be removed depends very sensitively on the rectification of the stellar spectrum, and we are continuing to refine our procedures to accomplish this correction more effectively.

3. FTS Spectra

The spectra we obtained are plotted as montages in Figures 1, 2, and 3 for the J, H, and K bands, respectively. This presentation emphasizes the very broad wavelength coverage that can be obtained with the FTS. Much of the 'noise' in these spectra is actually the sinc-function undulations ('ringing') due to the instrumental profile; in some cases (e.g., near He I 2.058μm in the K band), it is residual fringing due to interference between closely spaced telluric lines and the incoming starlight. Some artifacts resulting from incomplete removal of the telluric or solar spectrum are also present, but are generally very minor.

The strongest lines, most of which are due to H and He I, are identified at the top of the figures. Note in particular the two lines of the H Paschen series (P: $n \rightarrow 3$) in the J band; high members of the H Brackett series (Br: $n \rightarrow 4$) in the H band and Brγ in the K band; and high members of the H Pfund series (Pf: $n \rightarrow 5$) in the red part of the K band (where artifacts of incomplete telluric removal are also visible as very narrow emission spikes). The montages show the expected strengthening of the H absorption spectrum with later spectral type, and the loss of He I absorption features near B8–B9. The presence of He I 1.083μm in the spectrum of HD 160529 suggests that it is hotter than the A3 Iae classification given by the Bright Star Catalogue. Its spectrum is generally similar to that of β Ori, which supports the classification of B8–9 estimated by Sterken et al. (1991).

In addition to the absorption-line spectrum, the montages show that strong stellar-wind features are frequently present in the near-IR spectra of luminous stars. Indeed, as originally noted by McGregor, Hyland & Hillier (1988), the IR spectrum of the extreme hypergiant HDE 316285 is completely dominated by emission and P-Cygni profiles, including some strange flat-topped profiles of Fe II and Mg II. The LBV HD 160529 also exhibits striking, narrow P-Cygni profiles in He I 1.083μm, Pγ, Pβ, and weakly in Brγ.

Detailed modelling of these IR emission features provides a great deal of information about the properties of stellar winds. Figure 4 illustrates preliminary model fits to the strategic H and He lines of HDE 316285. The model profiles in Fig. 4 were calculated with the 'unified' model-atmosphere program described by Hillier (1990), and represent part of a collaborative effort with D. J. Hillier and P. A. Crowther to obtain refined estimates of the stellar-wind parameters of this extreme object. The stellar parameters derived from the IR lines are consistent with those determined from detailed fits to the optical spectrum. This

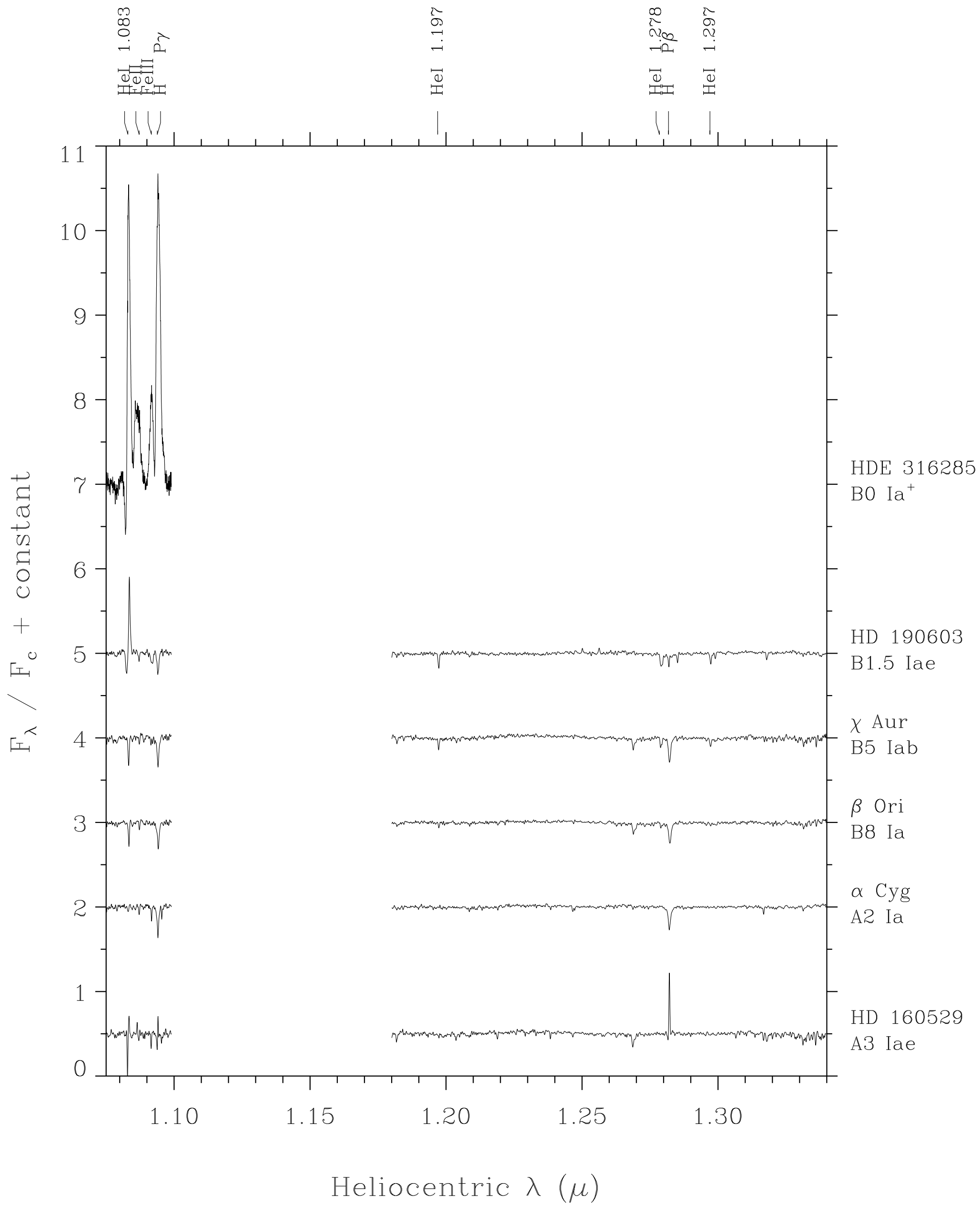

Figure 1. Montage of FTS spectra in the *J* band. Identifications for the strongest lines are indicated. The region between 1.10 and 1.18μm suffers from very strong telluric contamination and has been omitted. HDE 316285 was only observed with a narrow-band filter. Note the narrow P-Cygni profiles in the spectrum of HD 160529.

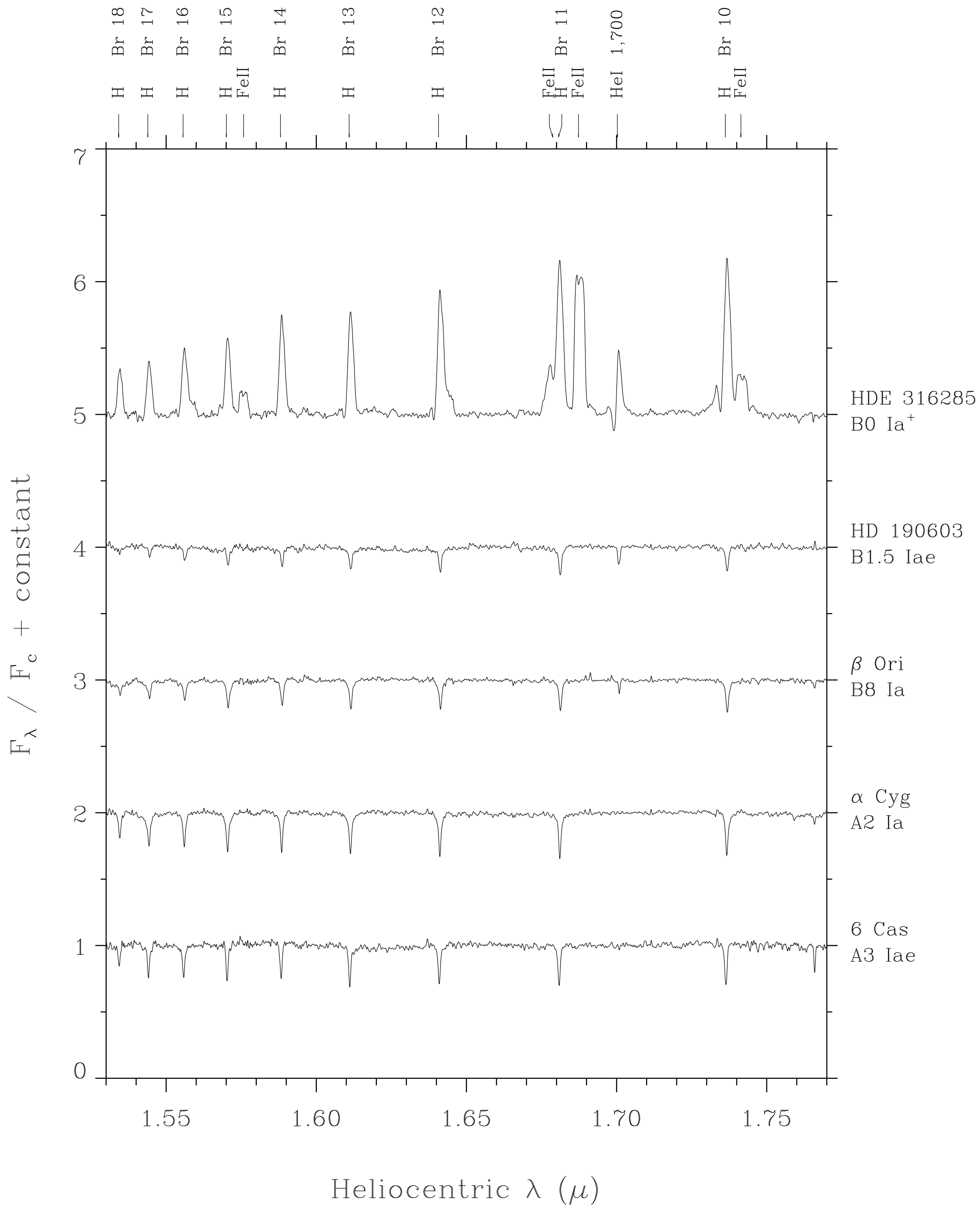

Figure 2. Montage of FTS spectra in the H band, which is dominated by the higher members of the Brackett series of hydrogen. Note the disappearance of He I 1.700μm between spectral types B8 and A2.

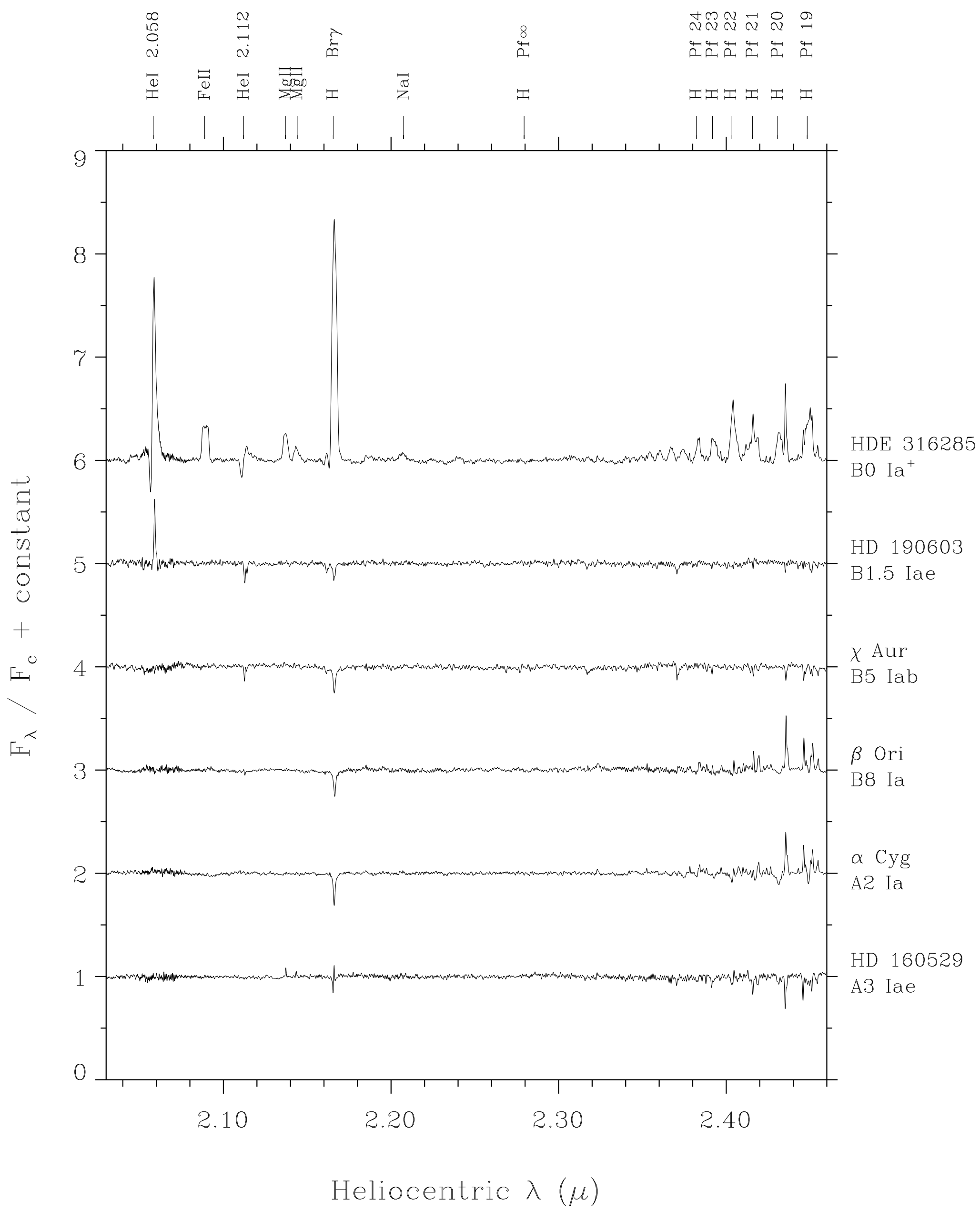

Figure 3. Montage of FTS spectra in the K band. Despite incomplete removal of the strong telluric contamination between 2.40 and 2.46μm, the high members of the Pfund series can be seen in emission for HDE 316285 and in absorption for α Cyg and HD 160529. Note the narrow P-Cygni profile at Brγ for HD 160529.

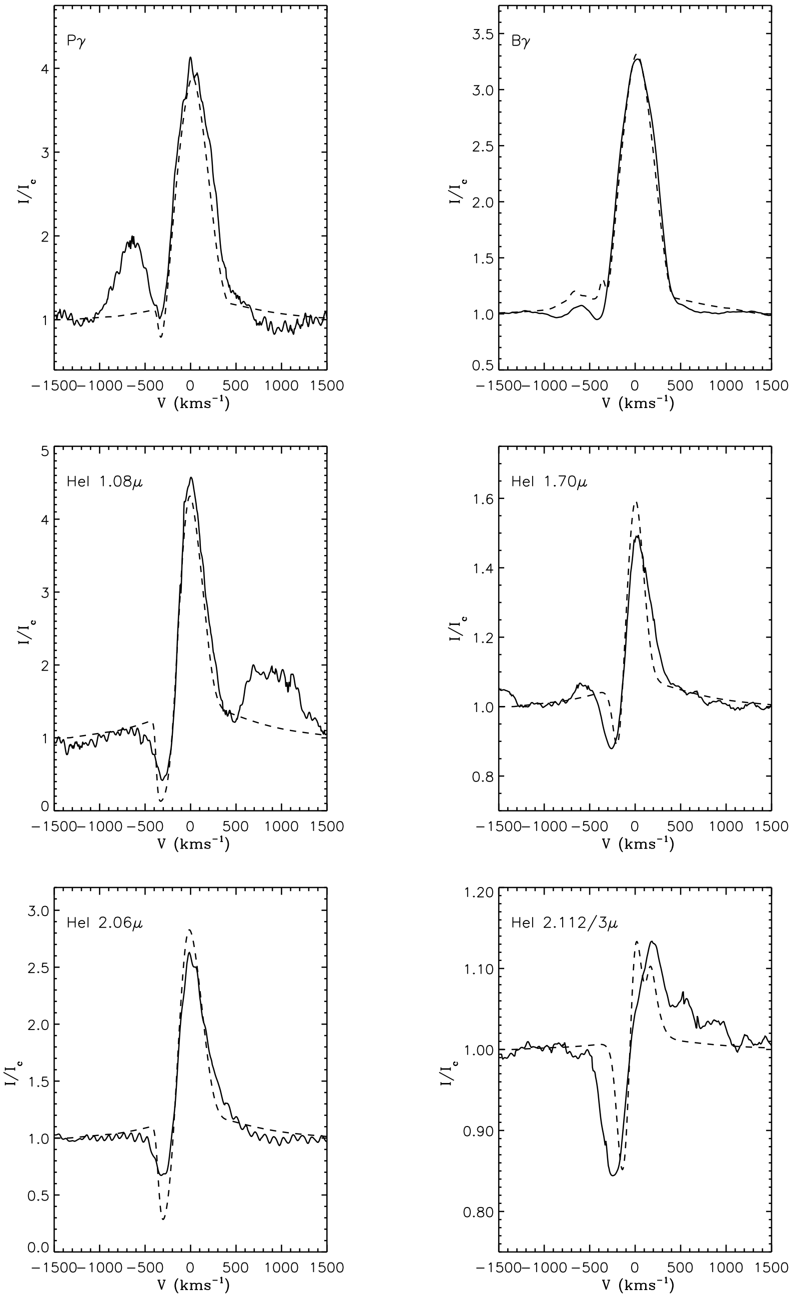

Figure 4. Comparison between computed (dashed) and observed (solid) profiles of H and He wind lines in the spectrum of HDE 316285 for a unified model atmosphere with $L_\star = 2.75\times10^5\,L_\odot$, $T_{\rm eff} = 15.3\,$kK, $R_\star = 75\,R_\odot$, He/H = 0.67, and $\dot{M} = 2.4\times10^{-4}\,M_\odot\,{\rm yr}^{-1}$.

agreement underscores the tremendous potential of high-quality near-IR spectra for quantitative analysis.

4. Concluding Remarks

On the basis of this pilot study, we conclude that the FTS is an excellent instrument for high-resolution IR spectroscopy of hot stars. In particular, its very broad wavelength coverage makes it ideal for surveys of bright targets. Unfortunately, follow-up work based on this study is not likely, since the FTS at CFHT is probably nearing the end of its lifetime. In view of the unique capabilities of this instrument, the last decade would therefore appear to represent a missed opportunity for surveying the spectra of hot stars in the near-IR. Nevertheless, the prognosis for this field is very good, since the next generation of high-resolution IR grating spectrographs will soon be available. Careful modelling of the spectra obtained with these instruments promises many new opportunities for determining the properties of the photospheres and stellar winds of hot stars.

Acknowledgments. We would like to thank Dr. David Bohlender for his outstanding support of our run. Our work has been supported by the Max-Planck-Institut für Astrophysik in Garching (A.W.F.), DFG grant Pu 117/3–1 (A.W.F.), and DARA under WE2–50 OR 9413 6 (F.N.). This research has made use of the SIMBAD database, which is operated at CDS, Strasbourg, France. The NSO/Kitt-Peak FTS data used here were produced by NSF/NOAO.

References

Hillier, D.J., 1990, A&A, 231, 116

Hoffleit, D., Jaschek, C., 1982, The Bright Star Catalogue, Fourth Revised Edition (Yale University Observatory, New Haven)

Johnston, S., 1991, Fourier Transform Infrared: A Constantly Evolving Technology, (Ellis Horwood, New York), p. 249

Livingston, W., Wallace, L., 1991, An Atlas of the Solar Spectrum in the Infrared from 1850 to 9000 cm^{-1} (1.1 to 5.4 microns), NSO Technical Report #91–001 (NOAO, Tucson)

Maillard, J.-P., Michel, G., 1982, in Instrumentation for Astronomy with Large Telescopes (IAU Coll. 92), ed. C.M. Humphries (Reidel, Dordrecht), p. 213

McGregor, P.J., Hyland, A.R., Hillier, D.J., 1988, ApJ, 324, 1071

Ridgway, S.T., Brault, J.W., 1984, ARA&A, 22, 291

Ridgway, S.T., Hinkle, K.H., 1992, in High Resolution Spectroscopy with the VLT (ESO Conf. & Workshop Proc., No. 40), ed. M.-H. Ulrich, p. 213

Schnopper, H.W., Thompson, R.I., 1974, in Astrophysics: Optical and Infrared (Methods of Experimental Physics, Vol. 12, Part A), ed. N. Carleton (Academic Press, New York), p. 491

Sterken, C., Gosset, E., Jüttner, A., Stahl, O., Wolf, B., Axer, M., 1991, A&A, 247, 383

Wallace, L., Hinkle, K., Livingston, W., 1993, An Atlas of the Photospheric Spectrum from 8900 to 13600 cm^{-1} (7350 to 11230Å), NSO Technical Report #93–001 (NOAO, Tucson)

Discussion

Drew: What has this instrument got that other systems available since the 1980s, which seemed to be limited by seeing changes, didn't have?
Fullerton: I think the clever thing about this one is that it uses phase modulation instead of a rotating chopper to deal with atmospheric scintillation. Also, sky removal is facilitated by automatic beam-switching between the twin detectors; even in the thermal IR there is no problem.
Hanson: I wanted to make a general comment that Time Allocation Committees concerned with IR spectroscopy have historically tended to be supportive of studies of relatively low-mass stars at the expense of high-mass stars. When Peter [Conti] and I started on my thesis work it took years to get past the TACs.
Fullerton: That's a fair comment. Of course, it's our job to swing TACs!
Barlow: FTS has many advantages, but a disadvantage is in the thermal infrared, longwards of about 2.3μm, you get the background from the entire bandpass – with a grating you just get the background in that resolution element.
Fullerton: Exactly, but subtracting the background as you go helps.