Exoplanet Research with the Advanced Fiber Optic Echelle

S.G. Korzennik¹, T.M. Brown², A.R. Contos¹, S. Horner³, S. Jha¹, T. Kennel², M. Krockenberger¹, P. Nisenson¹, and R.W. Noyes¹

Abstract:
The AFOE is a fiber-fed bench-top echelle spectrometer installed at the Mt. Hopkins 1.5 m telescope for research in exoplanets, asteroseismology, and other topics requiring precise radial velocity measurements. Here we describe the instrumentation, observing programs, and data reduction techniques for exoplanet research with the AFOE. We also summarize recent results of our search for and characterization of exoplanets. Further information on the AFOE can be found on the Web at http://cfa-www.harvard.edu/afoe.

1. Introduction

The Advanced Fiber Optic Echelle (AFOE) is a joint project of the Smithsonian Astrophysical Observatory (SAO) and the High Altitude Observatory (HAO). The instrument, a high resolution fiber-fed, bench-mounted echelle spectrograph, is installed at the 1.5-m telescope of the Whipple Observatory at Mt. Hopkins, Az. The spectrograph was designed to measure stellar radial velocities to a precision of a few m s⁻¹. A major scientific goal of this project, emphasized here, is extra-solar planet detection and characterization; other applications of the AFOE include: asteroseismology of Sun-like stars, asteroseismology of other stars, (e.g., δ Scuti, red giants, ...), and the study of Cepheids and RR Lyrae stars.

1.1. Instrument Description

To achieve a precision of a few m s⁻¹, the AFOE was designed both to achieve intrinsic high radial velocity precision, and to include two stable wavelength references.

Requirements for Very High Radial Velocity Precision. The following considerations have been included in the design of the AFOE:

- Mechanical stability: vibration isolated optical table mount, and fiber-coupled to telescope Cassegrain focus.

¹Harvard Smithsonian Center for Astrophysics
²High Altitude Observatory
³Penn State University

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• Thermal insensitivity: low thermal expansion quartz rods as spacers for critical dimensions; thermal enclosure with active control feedback loop; vertical temperature gradient to minimize spectrograph seeing effects.

• Minimal point spread function (PSF) variations: fiber optics scramble star image; double-scrambling for 1 m s\(^{-1}\) precision (for asteroseismology).

• High spectral resolution: echelle spectrograph, \(R \sim 50,000\).

• Record many spectral lines: cross-dispersion (24 orders) on a 2K \(\times\) 2K CCD detector.

• High throughput: efficient optics, thinned back-lit and AR coated CCD; tip-tilt mirror under development to minimize guiding errors.

• Large stellar flux input: use a 1.5-m telescope (optics designed to accept input from up to 2.5 m); emphasize observations on stars with \(V < 7\).

The Wavelength Reference  Even with all stability precautions, residual motions exist at the sub-pixel level, on all time scales from milliseconds (seeing) to years. Therefore, a wavelength reference is needed to provide both instantaneous and long-term corrections for instrumental and atmospheric effects. Two different methods have been used by most groups, both are incorporated in the AFOE:

• Record simultaneously a Th–Ar spectrum next to the stellar spectrum: the Th–Ar spectrum spans the entire spectral range (efficient use of starlight), provides good short-term stability, \textit{but} goes through an adjacent hence not identical optical path; hence it has a slightly different PSF. Also, the emission lines are sparse and unevenly spaced.

• Insert an iodine (I\(_2\)) gas cell in the stellar beam: the reference PSF is identical to the stellar PSF (and so can be precisely calibrated out), I\(_2\) cell is stable on long time scales, \textit{but} I\(_2\) lines span only 5000–6000 Å region.

Currently, the AFOE exoplanet detection program uses the I\(_2\) cell as its wavelength reference (optimize long term precision) while the AFOE asteroseismology program uses the Th–Ar as wavelength reference and the double scrambled fiber (optimize short term precision).

1.2. Current Capabilities of the AFOE Instrument for Extra-Solar Planet Research

The photon-limited Doppler precision (PLDP), for a \(V = 5\) sun-like star, in 20 minutes of integration, is about 5 m s\(^{-1}\). Our actually-attained precision is about 1.5 \(\times\) PLDP, or about 8 m s\(^{-1}\) for a \(V = 5\) sun-like star, in 20 minutes of integration. Our long-term (month-to-month) instrumental stability is about 5 m s\(^{-1}\) (about 15 m s\(^{-1}\) prior to January 1997). This is further illustrated in the orbital fits presented in Figures 4 to 8, and in Figure 9. (See discussion below).

2. Planned Near-Term Improvements to the AFOE

Two significant near-term improvements to the AFOE are being currently developed:
1) A new AFOE “Front End”, that includes a tip-tilt corrector, allowing for more accurate guiding of the stellar image onto the fiber; the tip-tilt mirror has been designed to compensate for image motion up to about 10 Hz. We expect a factor of at least two improvement in throughput. This will be installed during the Fall of 1997.

2) A Fabry-Perot wavelength reference (FPR) system. The new FPR system has been designed to overcome two disadvantages of the current $\text{I}_2$ cell reference: a) that the $\text{I}_2$ absorption lines are useful only in the wavelength range about 5000 to 6000 Å (i.e., only about 40 percent of the AFOE full wavelength range); b) because of their dense spacing the iodine lines absorb significant starlight and hence lose useful RV information. To alleviate both of these limitations, the FPR system incorporates a Queensgate Fabry-Perot etalon, that is used in reflection. The etalon spacing is servoed by a Zeeman-stabilized laser\(^4\). This configuration places a series of regularly-spaced (at about 2 Å intervals) sharp absorption features throughout the entire spectral region. The FPR, described schematically in Figure 1, will extend the useful wavelength coverage with respect to the iodine cell, and will absorb less stellar flux than the $\text{I}_2$ cell, while still allowing determination of the instrumental PSF, and the wavelength scale.

![Figure 1. Schematic description of the FPR. The etalon is used in reflection to produce regularly spaced absorption lines, and monitored in transmission by a Zeeman-stabilized laser. In this configuration the same area of the etalon that is used to imprint the stellar spectrum is monitored by the stabilization servo loop.](image)

\(^4\)This laser has been shown to provide wavelength stability at least as good as 2 m s\(^{-1}\) over at least several years

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3. Data Analysis Methodology

The AFOE data analysis methodology consists of modelling the observed star plus iodine spectrum. This model is computed from a Doppler shifted reference star-alone spectrum, a very high resolution (Fourier transform spectrometer, $R \sim 400,000$) reference iodine spectrum, a parameterized representation of the wavelength solution to match the known iodine wavelength scale, a parameterized description of the instrumental profile (PSF), as well as a few parameters to account for residual scattered light and gain fluctuations. This model covers the complete wavelength range of each order, but some of the parameterization is set to be a function of the location along the order, namely the PSF is parameterized to vary along the dispersion direction.

We adjust the model parameters to best match the observations in the least-squares sense. From the parameterization of the Doppler shift, we obtain an estimate of the line-of-sight velocity of the star. This modeling is carried out independently for each order; the resulting velocities are averaged, and the scatter from the mean provides an estimate of the uncertainty.

When applied to a typical frame of AFOE observations, which has, for a 10 min integration on a $V = 5.4$, G2 star, a photon-limited signal-to-noise ratio (SNR) of 134, our current model gives residuals of 1.3 %, which is only 1.5 times the Poisson noise limited value of 0.75 % (see Figure 2).

For higher SNR calibration data (i.e., quartz lamp + $I_2$ for which the Poisson SNR was about 1000), the model gives residuals of 0.27 %, which is 2.7 times the Poisson limit of 0.10 % (see Figure 3).

![Graph](image)

Figure 2. Top to bottom: model, observations and residuals ($\times 5$), for a 10 min integration on a $V = 5.4$, G2 star.
4. Examples of Current Results

We have detected near-sinusoidal radial velocity variations of the G2 V star $\rho$ CrB, with amplitude 69 m s$^{-1}$ and period 39.9 days, (Noyes et al., 1997). Figure 4 shows the radial velocity observations and the orbital fit to data through June 1997. The implications are that $\rho$ CrB has a giant planetary companion with minimum mass $m \sin i$ of 1.1 $M_{\text{Jup}}$, in a near-circular orbit with radius 0.23 AU.

This orbital radius is too great for the planet to be “parked” by tidal forces or magnetospheric interactions as suggested for very close giant planets by Lin et al. (1996), and thus enliven the discussion of orbital migration as an explanation of formation and current location of extra-solar giant planets.

Some other examples showing the level of current accuracy of our data are given in Figures 5 to 8, showing radial velocity observations and orbital fits to the following stars with known companions: $\tau$ Boo, 51 Peg, 70 Vir, and HD 160346. For 51 Peg, where most of the observations predate 1996, an arbitrary month-
Figure 4. Orbital fit to AFOE observations (through June 1997) of ρ CrB ($V = 5.4$, G2 V).
Figure 5. Orbital fit to AFOE observations of $\tau$ Boo ($V = 4.5$, F7V).

Figure 6. Orbital fit to AFOE observations of 51 Peg ($V = 5.5$, G2IV).
Figure 7. Orbital fit to AFOE observations of 70 Vir ($V = 5.0$, G0 V).
Figure 8. Orbital fit to AFOE observations of the spectroscopic binary HD 160346 ($V = 6.52$, K3 V).
Figure 9. AFOE velocities for two known RV constant stars: \( \tau \) Cet \((V = 3.5, \text{G8 V})\) and \( \beta \) Aql \((V = 3.7, \text{G8 IV})\). Stability of the instrument has improved after January 1996 (dashed line).
to-month offset was applied (the RMS of these offsets is about 33 m s$^{-1}$). For 70 Vir and HD 160346, where the fit is poorly constrained by the limited number of points, we used values close to published orbital parameters as initial guesses. Figure 9 illustrates the AFOE results for two stars known to be RV constant: $\tau$ Cet and $\beta$ Aql.

5. Current and Planned Extra-Solar Planet Research Program

The AFOE currently observes on about 7 nights per month, primarily for extra-solar planet detection. Our observing list consists of about 100 F,G, and K dwarfs, with $V \leq 6.75$, chosen to complement the observing lists of other groups capable of radial velocity measurements at 10 m s$^{-1}$ precision or better. Our methodology is to observe stars initially several times per observing run, on several successive observing runs. If significant (short-term) variations are seen, we continue this pattern; otherwise we reduce the frequency to several observations per year to monitor possible long-term variations. The data are usually reduced within one day, to aid in immediate planning of new observations.

Upon implementation of the new “Front End” and the new Fabry-Perot Reference, we can in principle gain an order of magnitude in detection efficiency, permitting attained precision of 5 m s$^{-1}$ on a $V = 7.5$ star in 30 minutes of integration.

We plan to continue AFOE extra-solar planet research in this way for at least the coming three years.

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