The AFOE Program of Extra-Solar Planet Research

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Abstract. We describe the program for detection and characterization of extra-solar planets using the Advanced Fiber Optic Echelle (AFOE) spectrograph, developed at Mt. Hopkins Observatory jointly by SAO and HAO. The AFOE is capable of obtaining radial velocity precision better than 10 m s\(^{-1}\) on relatively bright stars, and has produced data confirming the low mass companions to 51 Peg and \(\tau\) Boo. We describe the current observing program for monitoring a number of solar-like stars.

1. Introduction

The Advanced Fiber Optic Echelle (AFOE) spectrograph is a recently-developed instrument designed for the measurement of precise stellar velocity shifts. Its scientific motivation is both extra-solar planet research and asteroseismology of sun-like stars. The AFOE is located at the 60-inch Tillinghast telescope of SAO's Whipple Observatory on Mt. Hopkins, Arizona, in a thermally-isolated room adjacent to the telescope, and is fed by optical fibers from the telescope focal plane. The spectrograph optics are bench mounted, vibration-isolated, and enclosed in a thermally insulated box which employs a small vertical temperature gradient to eliminate convection. Spectra are produced by a cross-dispersed echelle on a 2048\(^2\) CCD with 15 \(\mu\)m pixels. Continuous wavelength calibration is provided by an I\(_2\) absorption cell that may be interposed in the telescope beam, as well as by an emission lamp which places a Th-Ar spectrum adjacent to the stellar spectrum through a second fiber continuously during the exposure. Spectral coverage is about 55\% of the region between 390 nm and 700 nm, in 24 spectral orders. The spectral resolution is adjustable between 32000 and 70000 through a variable entrance slit. A detailed description of the AFOE is provided by Brown et al. 1994.

The radial velocity precision currently obtainable by the AFOE depends on the application. For asteroseismology, where relevant timescales are tens of minutes or less, the AFOE has obtained short-term precision on bright stars of about 2 m s\(^{-1}\) (Figure 1). To obtain this precision we use the Th-Ar spectrum as a wavelength standard, because
Figure 1. Radial Velocity of α Boo after ephemeris subtraction. The 2.2 m s\(^{-1}\) rms deviation of the residuals measures the radial velocity noise in the data.

the Th-Ar lines span the entire spectral range of the AFOE data and thus facilitate correcting all of the data for short-term instrumental effects that enter at the few m s\(^{-1}\) level.

For longer intervals (night to night and month to month), variations in relative line intensities in the Th-Ar emission lamp complicate its use as a velocity reference at levels better than 10 to 15 m s\(^{-1}\), and so for our planet detection work to date we have concentrated on using the I\(_2\) cell. Our method of analysis of the I\(_2\) data is similar but not identical to that described by Butler et al. (1996). Our reduction algorithms are still under development. Currently, the precision and night to night stability of the radial velocity zero point are better than 10 m s\(^{-1}\) for a 10-minute integration on a \(V = 5\) sun-like star. However, from one run to another the stability of the velocity zero point has an rms variation of about 20 m s\(^{-1}\). We expect to bring all of the above figures to the 5 m s\(^{-1}\) level in the near future, as our software matures.

2. AFOE Monitoring Program of Candidate Stars

The AFOE extra-solar planet program is currently devoted to regular monitoring of about 100 F, G, and K dwarfs, generally with magnitude less than about 7. Of these, the great majority are stars for which we are actively seeking evidence of low-mass companions; about 8 are stars found in the literature to be apparently non-varying, which we are following to establish the AFOE long-term radial velocity stability, and a few are stars with already-reported companions for which we hope to get better constraints on their orbits, or possible second companions.

Currently, the AFOE is scheduled for observations on about 75 nights per year, always during lunar bright time and hence at near-monthly intervals. For the stars which are candidates for new detections, our philosophy is to observe them several times during each of several consecutive runs, to see if there are short-term radial velocity variations visible at the level of order 20 m s\(^{-1}\) or greater. If after several such runs the star appears to be non-varying at this level, we plan to place the star at a reduced level of monitoring to make room for additional stars. In this way we hope
to obtain useful data on several hundred candidate stars in the course of the next five years.

3. Results of Precise Radial Velocity Monitoring of Planet Candidate Stars

Figure 2 shows our data on 51 Peg. As noted by Noyes et al. (1995) and Kennelly et al. (1995), we confirm the sinusoidal radial velocity variation with period 4.23 days and amplitude about 59 m s\(^{-1}\) first reported by Mayor and Queloz (1995) and also confirmed by Marcy et al. (1997). The data in Figure 2 span almost one year, and show that the phase is constant over at least that length of time.

Figure 3 shows our data for \(\tau\) Boo. These results confirm the period of 3.3 days, amplitude of 469 m s\(^{-1}\) and phase of the essentially sinusoidal radial velocity variation of this star, as found by Butler et al. (1997).

Of other stars on our observing list, several show variations significantly larger than expected based on the precision values quoted above. These are under active investigation to determine whether the data are consistent with a Keplerian orbital fit.

4. AFOE Monitoring of Solar Radial Velocity Variations

The ultimate limits of detection of radial velocity variations due to extra-solar planets may be imposed by convective and other velocity inhomogeneities in the stellar photosphere, known to be produced by magnetic activity. These limits appear to depend on the spectral type and age of the star (e.g., Saar and Donahue 1997). To explore this dependence, it would be very useful to monitor the changing apparent radial velocity for a star with known true radial velocity over times with differing levels of magnetic activity. The Sun, while relatively inactive, is nevertheless a good candidate for such
monitoring because its true radial velocity is precisely known, and furthermore any observed changes in apparent radial velocity can be correlated with other well-observed solar magnetic variations, thus aiding in understanding and quantifying the physical mechanisms involved. The AFOE has a solar feed which allows monitoring the apparent radial velocity on the Sun on a daily basis. (Effects due to non-uniform atmospheric transmission across the extended rotating solar disk can be minimized by averaging observations over a time interval centered on the time of day when the rotation axis of the Sun is vertical in the sky.) We plan in the near future to automate the acquisition of daily solar radial velocity measurements, and begin acquiring a record which should extend through the coming solar magnetic activity maximum.

References