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A New Doppler Radial Velocity Machine at Kitt Peak for Extrasolar Planet Searches

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In August 2002, a new, compact, efficient, and low-cost interferometric instrument for high-precision Doppler radial velocity measurements was successfully demonstrated at the KPNO 2.1-meter telescope. It has confirmed the existence of a planetary companion around 51 Pegasus. This first-discovered nearby extrasolar planet was originally detected by Dr. Mayor's group in 1995, using a state-of-the-art echelle instrument. The new interferometric instrument, built by a Penn State team led by Prof. Jian Ge, is called the Exoplanet Tracker (ET). Team members include Penn State graduate students Suvrath Mahadevan and Julian van Eyken, undergraduate student Curtis DeWitt, and Jet Propulsion Laboratory collaborator Dr. Stuart Shaklan.

The instrument consists of a Michelson-type interferometer with fixed optical path difference and a moderate-resolution spectrograph, and is similar to the wide-angle Michelson interferometer being used in the Global Oscillation Network Group (GONG) project for high-precision Doppler radial velocity monitoring of the solar disk. The Doppler measurements are conducted by monitoring phase shifts of the interference fringes of stellar absorption lines, rather than tracking line centroid shifts as is done by current planet search echelle instruments. Instead of using a narrowband filter to monitor a single stellar line as in the GONG instrument, ET employs a moderate-resolution spectrograph to cover a broader band of wavelengths, thereby increasing sensitivity to faint stellar sources. The ability to use a moderate-resolution spectrograph opens up exciting possibilities, including multi-object capability, high throughput, and high sensitivity, all in a compact architecture that enables the development of low-cost radial velocity instruments with high thermal and mechanical stability. The first-light results of the prototype instrument are reported here.

First light of the Prototype Instrument at the KPNO 2.1-Meter

Penn State's ET is a Michelson-type interferometer with a 7-millimeter optical delay in one arm coupled with a f/7.5 medium-resolution spectrograph of R = 6000, operating in the first diffraction order. The interferometer consists of a commercial 50/50 cube beam splitter made of BK7 glass, two flat mirrors, and one BK7 parallel glass plate with 4-millimeter thickness. The glass plate is used to create a fixed optical path difference between the two interferometer arms. The interferometer output is fed into the spectrograph with an adjustable entrance slit. The spectrograph is a simple Czerny-Turner design, with two parabolas and a first-order reflecting grating from Richardson Grating Inc. The dispersed stellar fringing spectrum is recorded on the KPNO F3KB 1K × 3K back-illuminated CCD camera. The instrument is operated in the visible spectrum with a wavelength coverage of about 270 angstroms. During the first light, the instrument was setup on a vibration-isolated optical bench in the Coudé room of the telescope (see figure 1). An iodine calibration cell was placed in the path of the starlight to provide a calibration spectrum that could resolve instrument drifts from the real stellar drifts.

Figure 1: ET setup at the KPNO 2.1-meter telescope in August 2002, with Penn State student Curtis Dewitt in the background.

The interferometer path difference is maintained to $\lambda/1500$ by active control of a mirror backed by a piezoelectric transducer (PZT). The cavity drifts are monitored by a stabilized HeNe laser sent through the beam splitter off-axis and collected by a video camera. A LabView GUI compensates for the drifts by engaging the PZT and can also dial to other user-specified phases. The entire instrument was enclosed in an insulated box and heated from the top of the enclosure by an actively controlled heating blanket. This created stable stratification of the environment, with the optical

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plane heated to 24.0 ±1.5°C. A photomultiplier is mounted at the slit to monitor the fiber coupling and to monitor the stellar flux in order to be able to better correct for Earth's motion.

The instrument was coupled to the telescope using a 200-micron optical fiber at f/6. The efficient coupling of the fiber to the 2.1-meter telescope was achieved with the excellent Penn State fiber feed built in the 1980s by Larry Ramsey. Though the 200-micron fiber was not exactly matched to our instrument slit size, it was chosen as a compromise to prevent losing too much starlight from seeing variations. The need to measure the interferometer fringes in the nondispersion direction makes it necessary to spread the light out, so the starlight was spread over 300 pixels in the nondispersion direction by inserting a cylindrical lens in the beam before the interferometer. This had the additional advantage of being able to collect photons from bright stars without saturating the CCD.

During the first-light engineering run, a set of RV stable stars as well as stars with known planetary companions were observed. The observed stars include eta Cas, 31 Aql, tau Ceti, HD209458, 51 Pegasus, upsilon Andromedae and Arcturus. Although more than 30 percent of the photons were lost at the spectrograph entrance, the net detection efficiency from above the atmosphere to the detector was about 4 percent with the iodine cell in the beam, and about 6.5 percent without. The measured total instrument throughput with wide slit (from the telescope fiber output to the detector) was 19 percent. Thus, the efficiency of this prototype is already comparable to current, state-of-the-art echelle instruments.

First Results from the KPNO 2.1-Meter

After spending a few days installing and aligning the instrument, a large amount of engineering data were collected to calibrate and perform initial instrument tests. As is always the case when setting up an instrument for the first time at a new telescope, there were various unanticipated problems to overcome. Nonetheless, some exciting results were obtained with ET, and a great deal was learned about the environment in which it is to work.

The reduced data from the Kitt Peak run represents the first-ever planet detection using this totally independent Doppler technique. Figure 2 shows the radial velocity data obtained over several nights. Overplotted is the expected curve extrapolated from previous measurements of 51 Peg by Marcy's group. Although the scatter about the curve is still larger than anticipated, a good match was found between the ET data and previous echelle results, with a 1-σ in the residuals of about 23 meters per second. Figure 3 demonstrates short-term stability, looking at eta Cas (an RV stable star) over a period of about one hour. The standard deviation in these short-term measurements is only 2 to 3 meters per second. This is the most stable results from Ge's group so far, indicating that this new small, and low-cost interferometric instrument also has the potential to provide Doppler precision similar to that of the state-of-the-art, large and expensive echelle instruments.

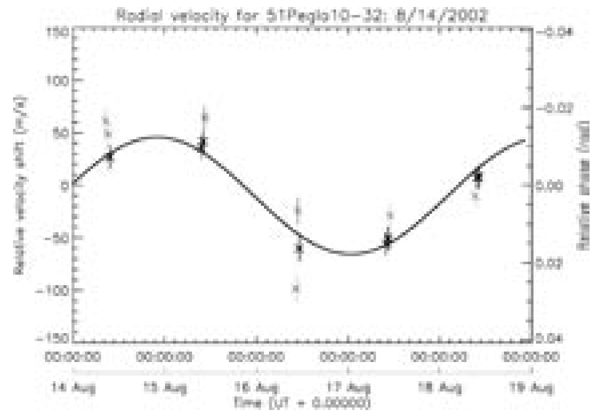

Figure 2. RV data obtained for 51 Peg, corrected for Earth's motion, along with the curve predicted from previous measurements by Marcy's group. The standard deviation in the residuals is ~23 meters per second (reduced χ^2~2.56, implying that there are still systematic errors that need to be tracked down).

The results shown are preliminary, and the data reduction software is still under major development. Among the particular problems encountered was significant detector drift. As the liquid nitrogen in the CCD dewar evaporated over time, the moment of the dewar slowly changed and caused a drift of the image on the detector. The larger pixel size of the CCD detector used in previous lab tests at Penn State had prohibited this problem from occurring in any obvious way before. The combination of the small pixel size of the new detector, the moment change, and the inevitable disturbance caused by refilling the dewar every half day led to an image drift of several pixels over the period of a day. Simulations show that this can easily create systematic errors of the order of hundreds of meters per second, and so the software has been modified to compensate for this effect, though this still needs some perfecting. The drift is suspected to be one of the major causes of the large scatter seen in current results, over and above the error bars, which represent the internal errors from the fringe phase and visibility measurements. This problem is a particular focus of the software development at the moment, especially since image drifts will be inevitable over the long term.

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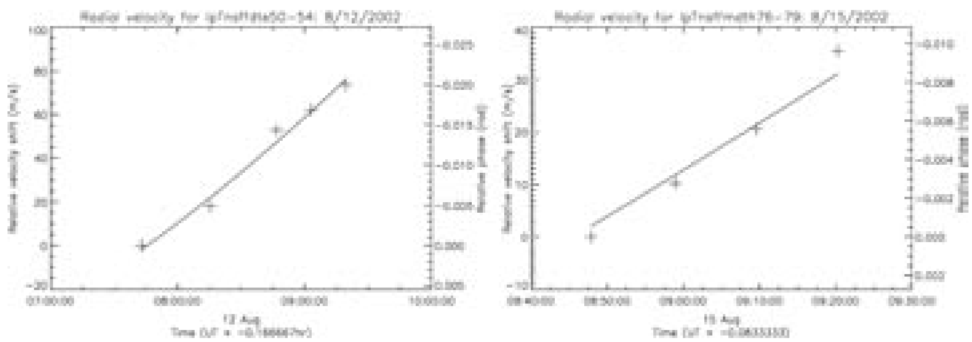

Figure 3. Short-term data obtained for eta Cas, an RV stable star. The solid line shows the expected curve due to the diurnal motion of Earth. 1σ residuals are ~3.7 meters per second and 2.9 meters per second respectively.

The data also suffered from aberration of various forms in the raw data images, in large part due simply to having a limited time frame for aligning the instrument properly. In order to reduce errors due to aberration, the data shown here is taken from approximately only the central third of the raw image frames obtained (in the slit direction). In principle, it should be possible to reduce the other sections independently and average the results together to further improve results.

Future Prospects

The team is still learning about the idiosyncrasies of ET and about the environment in which it will be working, and there is still considerable work to be done. They anticipate significant reductions in the systematic errors, and a dramatic increase in the throughput by about four times via instrument modifications (including replacing the grating with a Volume Phase Holographic Grating and utilizing both output beams from the interferometer).

Once ET is working robustly, we plan to install an instrument permanently at the Kitt Peak 2.1-meter and begin a small-scale survey for planets around stars that are too faint to have been investigated before. It will eventually be opened for public use, giving astronomers access to a powerful and highly competitive tool for high-precision radial velocity measurements of faint objects. The potential applications of such a tool go beyond simple planet hunting: it will be extremely useful in the field of asteroseismology, and could even be used in cosmological applications.

More excitingly, once the 2.1-meter setup is fully operational, they intend to build a multi-object version of ET, utilizing the fact that its single-order operation allows the fitting of multiple spectra onto a single detector. Combining this with HYDRA on the WIYN telescope, they will have an instrument ideally suited toward rapid deep sky surveys for extrasolar planets, in a manner impossible until now. The potential increase in the sample of known planetary companions could open a whole new window on the field of extrasolar planet studies.

The Penn State team would especially like to thank KPNO Director Richard Green, KPNO staff Skip Andree, Daryl Willmarth, Bob Marshall, John Glaspey, Jim Hutchinson, and many others for their excellent support and practical assistance during our time at the Kitt Peak 2.1-meter telescope.

Observing Opportunity on Himalayan Telescope

Our colleagues at the Indian Institute of Astrophysics have asked us to share an announcement of opportunity for observing with the 2-meter Himalayan Chandra Telescope. Time will be offered on their faint-object spectrograph and camera, HFOSC. Observers must be present at the remote operations center near Bangalore. **Proposals are due 15 March 2003.** For information, see *www.iiap.ernet.in/iao/cycle1.html.*