Iodine-Cell Spectroscopy at Okayama Astrophysical Observatory: First Results

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Abstract

Toward the aims of spectroscopically searching for planetary systems around stars, or detecting oscillations of solar-type stars for stellar seismology, we have started an experimental project of very precise determinations of stellar radial velocity variations based on the iodine-cell (I2 cell) technique at Okayama Astrophysical Observatory. We here report on the first preliminary results of test observations for two planet-harboring stars (υ And and τ Boo) based on data obtained by using the newly developed I2 cell and processed with a practical and quick analysis method. We confirmed that the internal statistical error can be as small as 5–6 m s⁻¹ at best. Then, the resulting radial velocity solutions turned out to be in reasonable agreement with the well-established predicted variations over a time span of 4–5 days; the O − C deviations indicate that a short-time-scale precision of ∼ 15 m s⁻¹ has been accomplished in a practical sense.

Key words: instrumentation: iodine cell — stars: individual (υ And, τ Boo) — stars: planet-harboring — techniques: radial velocities — techniques: spectroscopic

1. Introduction

Detections of a number of extrasolar planets (amounting to ∼ 70 up to now) by way of spectroscopically detecting an extremely slight Doppler wobble (i.e., cyclic radial velocity variation) of the parent star caused by an orbiting planet were counted as one of the most remarkable astronomical topics in the late 1990’s. In these sensational discoveries, the application of the iodine-cell technique, which was extensively developed mainly by the Lick group (see, e.g., Cumming et al. 1999, and the references therein), has played a substantial role in this field, along with the cross-correlation technique or the simultaneous Th–Ar calibration technique (e.g., by the Swiss group).

Meanwhile, at the same time, Okayama Astrophysical Observatory (OAO) was undertaking a replacement of the traditional coude spectrograph (C10 spectrograph) by the new High Dispersion Echelle Spectrograph (HIDES) (cf. Izumiura 1999), which was completed and made open to the public in 2000. The availability of HIDES has eventually made it possible to obtain stellar spectra with a spectral resolution of up to R ∼ 100000 and a wavelength coverage of ∼ 103 ˚A, which is a marked improvement compared to the case of the previous C10 spectrograph (coude grating spectrograph with f/10 camera; R ∼ 20000–40000 covering only a few ten to hundred ˚A).

Motivated by this instrumental innovation, it was natural for us to start a new pilot project of “precise detection of very small radial velocity variation”, mainly because of being stimulated by the recent discoveries of extrasolar planets mentioned above (which was done by using an echelle spectrograph similar to HIDES), as well as because we are interested in detecting non-radial oscillations in solar-type stars (stellar seismology), which is generally even more difficult than discovering planets.

Toward this purpose, we decided to install an iodine-cell (i.e., a glass cylinder containing vapor of the I2 molecule inside, through which the starlight passes) as a supplementary instrument used with HIDES, in order to enable such a high-precision Doppler-shift measurement, which utilizes the fact that the spectrum of numerous I2 lines printed over the stellar spectrum can serve as a firm reference, and thus an inevitable instrumental shift can be eliminated.

The first experimental proto-type cell was completed in the summer of 1998, followed by test observations using the C10 spectrograph (before 2000) and HIDES (after 2000), where two bright planet-harboring stars, υ And and τ Boo, were chosen as the main targets. Then, the proto-type cell was replaced by a newly manufactured regular cell in the summer of 2000 (E. Kambe et al., in preparation), where (1) optically flat glass (to a precision of ≤ λ/4) was used for the cell in order to
suppress the optical effect to the lowest level, (2) the transmission efficiency was considerably improved by applying the coating to the cell surface, and (3) the amount of iodine was so carefully chosen as to attain the most optimum optical thickness of I₂ vapor toward accomplishing the highest possible precision; also, observations were further performed with it in the autumn of 2000. The main purpose of these observations, carried out over a period of two years, was to examine to which extent of the precision is actually accomplished in detecting radial-velocity variations, as well as to clarify any technical problems toward improving its accuracy. Now, in this paper, we report on the first results of these test observations, along with the adopted method of data processing.

A description of the I₂ cell is given in section 2, and the details of the observations are presented in section 3. We then describe our approximate and quick method of data analysis devised for this preliminary investigation in section 4, while comparing it with a more exact approach, such that used by the Lick group (e.g., Butler et al. 1996). The results obtained for ν And and τ Boo are presented in section 5, where the resulting radial velocity variations for these two stars are compared with the predicted curves computed from the published orbital elements in order to examine the attained precision. Section 6 is devoted to conclusions.

2. Iodine Cell

Our first iodine cell as a proto-type model was experimentally manufactured in 1998. It is essentially a hollow cylinder (with a diameter and a height of ~3 cm) made of pyrex glass, in which solid iodine is vacuum-packed. The cell was further rolled up by a carbon-cloth, an aluminium board, and nichrome wires of a thermostat. After the entire body was covered by thick styrofoam (working as an insulator) having two glass-covered windows enabling light to pass through the cell, the whole system was packed in a substantial steel-box, which was eventually placed in front of the entrance slit of the spectrograph at the f/29 coudé focus of the 188 cm reflector. The cell temperature (measured at the surface of the cell) was kept at 50°C by a thermostat with an accuracy of ±1°C, at which point almost all of the iodine inside the cell was vaporized. Since no coating was performed onto the glasses of the cell itself as well as of the windows, the transparency efficiency turned out to be rather poor, and about a half amount of the incident light was scattered, and thus lost, by this system. The in/out-setting of the cell during the observation was remotely controlled without any necessity of entering the coudé room.

3. Observations

3.1. Observed Frames and Data Reduction

Here, we describe the observations of ν And or τ Boo performed at three observational epochs. We hereinafter use the following terminology:

— “pure star” frame is the normal observation of a star without using the cell;
— “lamp+cell” frame is the exposure of the continuum source (tungsten lamp placed in the light-path at the entrance window of the coudé room) with the I₂ cell, which gives a spectrum of pure I₂ absorption lines; and
— “star+cell” frame, which corresponds to the observation of a star with the I₂ cell, yielding a composite spectrum of stellar and I₂ absorption lines.

In all cases, the data reduction was performed by using the IRAF software package in a standard manner. In each of the observations, exactly the same “wavelength vs. pixel” relation (derived from a comparison-line frame taken at the first day of the observing run) was applied to all of the frames obtained during the whole observational period, in order to ensure that the apparent wavelength shift of I₂ lines from frame to frame would be purely due to an instability of the spectrograph, and not to the difference in the wavelength calibration.

The S/N ratios of the resulting spectra in our observations differ from case to case, but are typically of the order of 100–200.

3.2. 1998 November Observation of ν And

Since HIDES was not yet available at this time, we used the conventional C10 spectrograph with a 1800 groove mm⁻¹ grating in the first order. This resulted in a spectrum with a reciprocal dispersion of 5 Å mm⁻¹ (corresponding to a spectral resolution of R ~ 30000 for a pixel size of 15 μm) at the detector (4096 × 200 pixel CCD developed at University of British Columbia), covering the wavelength region of 5100–5400 Å, though the longest wavelength part of several ten Å could not be practically used because of many bad pixels in CCD. While concentrating on observing ν And, we could obtain totally ~220 “star+cell” frames of 5–10 min exposures (along with the “pure star” frame and the “lamp+cell” frame) on 1998 November 11, 12, 14, and 15.

3.3. 2000 April Observation of τ Boo

We observed τ Boo on 2000 April 11, 12, 13, 15, and 16 with HIDES. The slit width was set to 200 μm (0″.76), corresponding to a spectral resolution of R ~ 65000. By using a single 4K × 2K CCD (13.5 μm pixel), the wavelength range of 4850–6050 Å was observed at one time, which sufficiently covers the important region where numerous lines of I₂ are confined (5000–6000 Å). About 40 “star+cell” frames of 30 min exposure were obtained along with the “pure star” and the “lamp+cell” frames.

3.4. 2000 October Observation of ν And

Unlike the above-mentioned two observations carried out with the proto-type I₂ cell, this observation of ν And with HIDES on 2000 October 18, 20, and 21 was performed using the newly developed iodine cell of much improved efficiency (cf. section 1), the details of which will be described elsewhere (E. Kambe et al., in preparation). The observed wavelength region was 5000–6200 Å and a slit width of 200 μm was adopted, as was done in the 2000 April observation. In total, 15 “star+cell” frames of 15 min exposure were obtained along with the “pure star” and the “lamp+cell” frames.

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while introducing a factor $\alpha$ the actually observed “lamp+cell” spectrum at 5260–5265 Å (instrumental profile) as free parameters to be adjusted, we [10-36] in Mihalas 1978] as the relation between the line-depth $\equiv \eta/\eta_0$ (“0” denotes the standard Kitt Peak National Observatory and kindly provided by Dr. G. W. Marcy. In modeling the spectrum by using this fiducial Lick-Hamilton cell), corresponding to the ratio of the optical continuum of the tungsten lamp.

3.5. Cell-Absorption Property and Spectral Resolution

In order to examine the property of the iodine cell (especially concerning the strength and purity of I$_2$ absorption lines) as well as to check the spectral resolution of the spectra, we first studied the “lamp+cell” spectra, which showed the absorption features of the I$_2$ lines superimposed on the background continuum of the tungsten lamp.

As a comparison standard, we invoked the Lick-Hamilton I$_2$ cell spectra of extremely high spectral resolution ($R \sim 400000$), which were obtained by the Fourier Transform Spectrometer of Kitt Peak National Observatory and kindly provided by Dr. G. W. Marcy. In modeling the spectrum by using this fiducial standard, we assumed Minnaert’s formula [see, e.g., equation (10-36) in Mihalas 1978] as the relation between the line-depth ($R$) and the line-to-continuum optical-depth ratio $\eta (\equiv \Delta \lambda) / \lambda$, while introducing a factor $\alpha (\equiv \eta / \eta_0)$ (“0” denotes the standard Lick-Hamilton cell) corresponding to the ratio of the optical thickness of the I$_2$ vapor lines between our cell and theirs.

Then, adopting $\alpha$, $\Delta \lambda$ (the shift to take into account the difference of the wavelength scale), and FWHM (of the Gaussian instrumental profile) as free parameters to be adjusted, we determined the solutions of these three variables, such as those yielding the best fit between the observed and simulated spectrum, based on the fitting algorithm described by Takeda (1995). The resulting (best-fit) adjusted spectrum and the actually observed “lamp+cell” spectrum at 5260–5265 Å are shown in figure 1 for the cases of the 1998 November observation (C10) and the 2000 April observation (HIDES) as demonstrating examples.

We can see from this figure that the absorption nature of our cell appears to be essentially the same as that of the Lick-Hamilton cell (i.e., no impurity species). The $\alpha$ values obtained as a by-product indicate that the optical thickness of our cell is somewhat (i.e., by several ten percent) larger than that of the Lick-Hamilton cell. According to the resulting FWHM values (4.5 km s$^{-1}$ and 9.7 km s$^{-1}$ for HIDES and C10, respectively), we confirmed that the expected spectral resolution of the spectrograph (65000 and 30000) had been correctly realized.

4. Method of Analysis

4.1. Basic Equations of Spectrum Modeling

In order to detect a very slight radial velocity variation of a star from the observed “star+cell” spectrum while eliminating any effect of inevitable mechanical instability, we had to construct a parametrized model for such a complex spectrum, based on which desired solution could be accomplished by finding the best fit between these two.

Since the details of this modeling are described in the papers of the Lick group [see, e.g., Marcy, Butler 1992; Valenti et al. 1995; Butler et al. 1996] and the ESO group (Endl et al. 2000), we give only a brief summary here.

The intrinsic stellar flux spectrum originating from a star, $S(\lambda)$, generally undergoes several kinds of modifications until observed by us as a detector output of the “star+cell” spectrum;

(a) wavelength shift due to the stellar radial velocity, $\Delta \lambda_s$,
(b) superposition of the absorption lines of iodine molecules expressed by the cell transmission function, $A(\lambda)$,
(c) instrumental blurring by the Point-Spread-Function of the spectrograph, $I(\lambda; a_1, a_2, a_3, \ldots)$ (where $a_1, a_2, a_3, \ldots$ are the variable parameters characterizing the instrumental profile),
(d) error caused by any mechanical instability of the spectrograph or by any optical distortion effect on a ray of stellar light (see, e.g., subsection 4.3), which we represent by an apparent (detector-position-dependent) wavelength shift, $\Delta \lambda_m$.

Namely, in a hypothetical ideal case without any mechanical shift, we would observe [as a combination of effects (a), (b), and (c)]

$$F_s(\lambda; \Delta \lambda_s, a_1, a_2, a_3, \ldots) \equiv I(\lambda; a_1, a_2, a_3, \ldots) \ast [A(\lambda)S(\lambda - \Delta \lambda_s)],$$

where “$\ast$” means the convolution.

Actually, however, what we detect more or less suffers from effect (d) as

$$F_s(\lambda; \Delta \lambda_s, \Delta \lambda_m, a_1, a_2, a_3, \ldots) \equiv F_s(\lambda - \Delta \lambda_m; \Delta \lambda_s, a_1, a_2, a_3, \ldots).$$

Consequently, the “star+cell” spectrum can be modeled by this $F_s(\lambda)$, which is characterized by the following parameters: $\Delta \lambda_s, \Delta \lambda_m, a_1, a_2, a_3, \ldots$. We can then determine the stellar radial velocity ($\Delta \lambda_s$) by simultaneously establishing the solutions of these parameters, which eventually accomplish the best fit between the model and the observation.

The detailed approach described above, which takes into account the condition/seeing-dependent variability of the
instrumental-profile, should be the best way to achieve the highest possible precision. However, it is not necessarily easy to be actually carried out because of the following problems:

— First, the intrinsic stellar spectrum, $S(\lambda)$, must be established in advance by deconvolving the instrumental profile from the “pure star” spectrum.

— Second, the true transmission function of the iodine cell, $A(\lambda)$, should be known based on an extremely high-resolution experiment (though we may use the Lick-Hamilton template spectrum as an approximate substitute; cf. subsection 3.5).

— Third, since it requires considerable computational operations, the solutions are obtained only after lengthy calculations on an efficient first-class computer.

As a matter of fact, although we have completed the development of software following this detailed approach, which will be described in a separate paper (B. Sato et al., in preparation) along with a discussion of the precision attained therewith, the computational burden demanded by this program turned out to be somewhat problematic from a practical point of view, especially when we need to analyze a large number of time-series frames.

4.2. Approximate Approach

Accordingly, in this report of our first results, we instead adopt an alternative approximate approach, which also yields solutions of sufficient precision (though inferior to the more detailed method described in the previous subsection) very quickly, even on an outdated computer of low efficiency.

In this practical method, what we need as reference templates are only those two actually observed spectra at any time in the observational period: namely, the “pure star” spectrum,

$$P(\lambda) \equiv I(\lambda) + S(\lambda),$$

and the “lamp+cell” spectrum,

$$Q(\lambda) \equiv I(\lambda) + A(\lambda).$$

We then approximately model the “star+cell” spectrum by a simple multiplication of $P$ and $Q$ while introducing two free adjustable (wavelength-shift) parameters, $\Delta \tilde{\lambda}_s$ and $\Delta \tilde{\lambda}_m$, as

$$\tilde{F}_s(\lambda; \Delta \tilde{\lambda}_s) \equiv P(\lambda - \Delta \tilde{\lambda}_s)Q(\lambda)$$

and

$$F_{s+m}(\lambda; \Delta \tilde{\lambda}_s, \Delta \tilde{\lambda}_m) \equiv \tilde{F}_s(\lambda - \Delta \tilde{\lambda}_s; \Delta \tilde{\lambda}_m).$$

Note that $\Delta \tilde{\lambda}_s$ in this case is interpreted as the relative difference of $\Delta \lambda_s$ between that of the “star+cell” frame in question and that of the reference “pure star” frame,

$$\Delta \tilde{\lambda}_s \equiv \Delta \lambda_s(\text{star + cell}) - \Delta \lambda_s(\text{pure star}).$$

Similarly, $\Delta \tilde{\lambda}_m$ is expressed as

$$\Delta \tilde{\lambda}_m \equiv \Delta \lambda_m(\text{star + cell}) - \Delta \lambda_m(\text{lamp + cell}).$$

Naturally, equation (6) is regarded as being an approximate version of equation (2).

In this modeling, there are two practical merits:

— First, there is no need to know any detailed information about $I(\lambda)$, $A(\lambda)$, and $S(\lambda)$.

— Second, the free parameters to be established are only two, $\Delta \tilde{\lambda}_s$ and $\Delta \tilde{\lambda}_m$. This means that the solutions are effected very quickly by using any kind of numerical algorithm of optimization problems, for which we adopted that of Takeda (1995) in this paper.

Figure 2 intuitively demonstrates (for three observational cases described in subsections 3.2–3.4) that the observed “star+cell” spectra can be satisfactorily simulated even by this approximate model. As a matter of fact, we show in section 5 that a sufficiently high precision can actually be realized even with such a simple approach.

Meanwhile, the evident drawback of this method is that the absolute radial velocity of a star can not be obtained any more, since $\Delta \tilde{\lambda}_s$ (appearing explicitly in this formulation) is the “relative” quantity, unlike $\Delta \lambda_s$ itself.

4.3. Averaging over Segments

The procedure described in subsection 4.2 was applied to each 5 Å spectrum segment, i.e., each of the subdivided portions of the whole spectra. Based on the result of $\Delta \tilde{\lambda}_s(i, t)$ for segment $i$ of a “star+cell” frame $t$ (i.e., observed at time $t$), we
obtain the solution of the (relative) stellar radial velocity $\tilde{v}(i,t)$ (with respect to the reference “pure star” frame) as

$$\tilde{v}(i,t) = c\Delta \lambda(i,t)/\lambda(i), \quad (9)$$

where $c$ is the speed of light and $\lambda(i)$ is the wavelength at the middle of segment $i$. In principle, each $\tilde{v}(i,t)$ can be averaged over all segments to obtain $\langle \tilde{v}(t) \rangle$ (the final solution of the radial velocity corresponding to frame $t$). However, since we found that each $\tilde{v}(i,t)$ shows a systematic dependence upon the position on the detector (i.e., on the wavelength within an echelle order, as well as on the echelle order), such a simple averaging over wavelengths could not be applied for the purpose of improving the precision. This situation is demonstrated in figure 3a (the case of a sample frame of $\nu$ And observed with OAO HIDES, as discussed in subsection 5.2), where the $\tilde{v}(i,t)$ values at each of the segments (for a selected representative frame $t$) are plotted with $\lambda(i)$.

The main cause of this effect may probably stem from the use of our actually observed “pure star” spectrum (taken without the cell) as a template, in order to model the “star+cell” spectrum (taken with the cell). Namely, the rays of the stellar light may have been slightly deflected by inserting the cell, which may have caused a delicate distortion of the echellogram on the detector (i.e., a slight change in the dispersion relation). Hence, the detector-position-dependent systematic effect observed in figure 3a may be interpreted as being due to such a distortion effect on the dispersion relation. Though a reasonable way to remove such a systematic effect may be to find accurate corrections to the dispersion relation, we dealt with this problem in a somewhat different manner, as described below.

Such a systematic effect appears to be position-dependent and to act nearly equally on all “star+cell” frames, as far as the spectrum at a given position of the detector is concerned. We, therefore, decided to invoke the differential velocity ($\delta \tilde{v}$) with respect to that of the reference epoch, instead of working on $\tilde{v}$ itself, which does not cause any serious problem, since we are interested in detecting the time variation of the radial velocity. Note that we have used the word “differential” in the time-like sense, since $\delta \tilde{v}$ is essentially the relative variation of the stellar radial velocity within an ensemble of many similar “star+cell” frames observed at various times. (This should be clearly distinguished from the word “relative” used in the definition of $\Delta \tilde{\lambda}$ in subsection 4.2, by which we indicated the comparison of a “star+cell” frame with the fiducial “pure star” frame.)

Let us suppose that the reference spectrum is that of the “star+cell” frame taken at time $t = 0$. Then, we define the differential velocity, $\delta \tilde{v}(i,t)$, for segment $i$ of a “star+cell” frame $t$ (relative to the “star+cell” frame 0) as

$$\delta \tilde{v}(i,t) \equiv \tilde{v}(i,t) - \tilde{v}(i,0), \quad (10)$$

Such calculated $\delta \tilde{v}(i,t)$ values are also plotted with $\lambda(i)$ in figure 3b, where we can clearly observe (by comparing figure 3a) that the systematic tendency has almost disappeared while showing a considerable reduction of the scatter. Consequently, each $\delta \tilde{v}(i,t)$ can be averaged over all segments to obtain $\langle \delta \tilde{v}(t) \rangle$ as

$$\langle \delta \tilde{v}(t) \rangle \equiv \frac{\sum_{i=1}^{N} \delta \tilde{v}(i,t) / N}{N} \quad (11)$$

as the final solution of the differential velocity for frame $t$ with respect to frame 0, where $N$ is the number of segments available. The probable error (p.e. $\equiv \sigma / \sqrt{N}$; $\sigma$ is the standard deviation) involved with this $\langle \delta \tilde{v}(t) \rangle$ is written as

$$\text{p.e.} \equiv \sqrt{\frac{\sum_{i=1}^{N} (\delta \tilde{v}(i,t) - \langle \delta \tilde{v}(t) \rangle)^2}{N(N-1)}}. \quad (12)$$

5. Results
5.1. Finally Adopted Data
All results which we discuss in this section are based on such established average $\langle \delta \tilde{v}(t) \rangle$ values of the differential velocities described above in subsection 4.3. We adopted the first “star+cell” spectrum in the observational period as the reference spectrum ($t = 0$). In averaging the segment solutions, we discarded those solutions of slow convergence or diverged ones, those showing appreciably large $\chi^2$ values (i.e., those
with an unsatisfactory fit), and those at $\lambda > 5800 \AA$ because of the influence of telluric lines.

5.2. $\nu$ And

We first discuss the results of $\nu$ And, which is known to be a system of three planets (Butler et al. 1999) with the main variation (due to companion b) showing a velocity amplitude of 73 m s$^{-1}$ and a period of 4.62 d. Based on the observational data described in subsections 3.2 and 3.4, we calculated $\langle \delta v(t) \rangle$. The results are plotted in figures 4a (C10 case in 1998 November) and b (HIDES case in 2000 October), where two predicted curves computed from the orbital elements of Butler et al. (1999) ($P = 4.6170$ d, $T_{\text{peri}} = JD 2450002.24$, $e = 0.034$, $\sigma = 83.0^\circ$, $K = 73.0$ m s$^{-1}$) and the recently updated values presented in (http://exoplanets.org/esp/upsandb/upsand.html) ($P = 4.6171$ d, $T_{\text{peri}} = JD 2450000.6383$, $e = 0.02$, $\sigma = 316^\circ$, $K = 70.2$ m s$^{-1}$) are also shown for a comparison (though these two theoretical curves are quite similar to each other). Also, for the latter case of the 2000 October observation, the resulting numerical values of $\langle \delta v(t) \rangle$ along with the corresponding probable errors and the heliocentric corrections are given in table 1.

The heliocentric correction for each frame, corresponding to the time just at the middle of the exposure, was computed with the help of the “rvcorrect” task in IRAF. $\langle \delta v \rangle_{\text{hel}}$ in column 4 is defined as $\langle \delta v \rangle + C_{\text{hel}}$. All velocity results (columns 2–5) are expressed in units of km s$^{-1}$.

The internal statistical error [i.e., equation (12)] for the 1998 November data (C10 spectrograph; $R \sim 30000$) turned out to be typically 50–60 m s$^{-1}$ (with $N \sim 40$), while that for the 2000 October data (HIDES; $R \sim 65000$) is 5–6 m s$^{-1}$ (with $N \sim 200$) as shown in table 1. We can see from both figures that, while the global tendency of the expected radial velocity variation is only ambiguously reproduced in the old case of the 1998 observation, where the r.m.s. deviation of $O - C$ is 73 ms$^{-1}$ (the quoted range is the 90% confidence limit), the situation was considerably improved in the 2000 October observation ($O - C$ deviation is 15 ms$^{-1}$), thanks to the much improved precision accomplished.

This result of significantly higher precision of the latter than the former can be interpreted in terms of the relation that the error is, roughly speaking, proportional to $R^{-1} \times N^{-1/2} \times (S/N)^{-1}$ (see, e.g., Campbell, Walker 1979). In any case, figures 4a and b suggest the superb efficiency of the new OAO echelle spectrograph (HIDES) compared to the conventional grating spectrograph (C10), i.e., a higher spectral resolution (larger $R$) and a wider wavelength coverage (larger $N$), which become manifest especially in this kind of observation aiming at high precision.

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**Table 1. Radial velocity results for $\nu$ And (2000 October).**

<table>
<thead>
<tr>
<th>JD (2450000+)</th>
<th>$\langle \delta v \rangle$</th>
<th>$C_{\text{hel}}$</th>
<th>$\langle \delta v \rangle_{\text{hel}}$</th>
<th>p.e.</th>
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</table>

* The observation time (in JD) given in column 1 corresponds to the middle of the exposure. $\langle \delta v \rangle$ and p.e. presented in columns 2 and 5 are the quantities defined by equations (11) and (12), respectively. The heliocentric correction $C_{\text{hel}}$ in column 3 was computed by using the “rvcorrect” task in IRAF. $\langle \delta v \rangle_{\text{hel}}$ in column 4 is defined as $\langle \delta v \rangle + C_{\text{hel}}$. All velocity results (columns 2–5) are expressed in units of km s$^{-1}$. 

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10 The experiment by Hatzes and Cochran (1992) suggested a slightly more steep $R^{-1}$-dependence of $\sim R^{-3/2}$ (per unit band-width); i.e., $R^{-1}$-dependence if the effect of band-width variation caused by a change in $R$ is taken into account (cf. their figure 1).
Table 2. Radial velocity results for τ Boo (2000 April).*

<table>
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<tr>
<th>JD (2450000+)</th>
<th>⟨δv⟩</th>
<th>C_hel</th>
<th>⟨δv⟩_hel</th>
<th>p.e.</th>
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</table>

* The meanings of the columns are the same as in table 1 (cf. the notes therein).

5.3. τ Boo

We next discuss the observations for τ Boo, which harbors a giant massive planet ($M \sin i = 3.9 \, M_J$) orbiting around this F7 V star with a short period of 3.3 d (Butler et al. 1997), and is known for the controversial detection of the reflected starlight by the planet (see, e.g., Collier Cameron et al. 1999, 2000; Charbonneau et al. 1999). Because of the massiveness as well as the proximity of the planet, it shows an extraordinarily large radial-velocity variation with an amplitude of 470 ms$^{-1}$.

Our observational results are presented in table 2. In this case, the probable error (p.e.) of each $\langle \delta v(t) \rangle$ turned out to be typically 10–15 ms$^{-1}$, which is about 2–3 times larger than the case of $\nu$ And (table 1) with a similar spectral quality ($R \sim 65000$ and $N \sim 200$). Presumably, this difference may be related (at least partly) to the different appearance of the spectral lines between these two stars; namely, according to Fuhrmann et al. (1998), τ Boo has an appreciably larger rotational velocity ($v \sin i = 15.6 \, k \, m \, s^{-1}$) than that of $\nu$ And (9.5 km s$^{-1}$), and thus the spectral lines of the former are generally wider/shallower than those of the latter, which we can easily recognize from figure 2 [compare panel (b) with panel (c)]. This must have contributed to a lowering of the precision in the case of τ Boo, since the accuracy depends on the sharpness (i.e., depth and width) of stellar spectral lines [cf. equation (1) in Campbell and Walker (1979)]. In addition, the fact that the number of strong lines is smaller in τ Boo ($T_{\text{eff}} \sim 6400$ K) compared to $\nu$ And ($T_{\text{eff}} \sim 6100$ K) may contribute to the difference in the precision.

Figure 5 shows (along with the observational data) two predicted curves computed from Butler et al.’s (1997) orbital elements ($P = 3.3128$ d, $T_{\text{peri}} = JD 2450234.45$, $e = 0.018$, $\sigma \varpi = 254$′′0, and $K = 469.0$ ms$^{-1}$ derived from observations of 1995 February through 1996 July) and the updated elements ($P = 3.312423$ d, $T_{\text{peri}} = JD 2450501.900$, $e = 0.017377$, $\sigma \varpi = 161$′′48, and $K = 466.392$ ms$^{-1}$ derived from observations of 1995 February through 2001 May; private communication with Dr. R. P. Butler). We can see from this figure that our observational plots are in reasonable agreement with the predicted curve calculated from the latest orbital elements (where the r.m.s. $O - C$ deviation is 28′′+6 ms$^{-1}$), while an appreciable systematic discrepancy is observed when compared with the curve corresponding to Butler et al.’s (1997) old elements. This clearly indicates the necessity of using elements as accurate as possible in this case.

6. Conclusion

We have started a pilot project of high-precision observations of the stellar radial-velocity variation by using an iodine-cell at Okayama Astrophysical Observatory, with the prospects...
of searching for planets around stars or detecting oscillations of solar-type stars.

For this purpose, a first I$_2$ cell as a proto-type model was experimentally manufactured, which was later replaced by the new cell of much improved efficiency. Test observations of two planet-harboring stars, $\upsilon$ And and $\tau$ Boo, were carried out by using them.

We adopted an approximate method of analysis, which can establish solutions with reasonably high precision (though inferior to the case of the more detailed approach) very quickly, and may be suitable for this kind of test analysis.

We were obliged to focus on the differential velocity variation relative to a reference frame because of the (detector-)position-dependent systematic effect.

A comparison of the results of $\upsilon$ And observed in 1998 and 2000 revealed that the internal statistical error turned out to be 5–6 m s$^{-1}$ in the latter case using a new echelle spectrograph (HIDES), which is considerably smaller than the former case of observing with the old grating spectrograph (50–60 m s$^{-1}$), manifestly showing the merit of higher spectral resolution and wider wavelength coverage of HIDES. The resulting radial velocity variations of $\upsilon$ And for the latter case turned out to be reasonably consistent with a prediction calculated with the published orbital elements of the Lick group (Butler et al. 1999 or ⟨http://exoplanets.org/esp/upsandb/upsand.html⟩ for more updated values). According to the $O-C$ r.m.s. deviation, we may state that a precision of $\sim 15$ m s$^{-1}$ is accomplished for this 2000 October case of $\upsilon$ And in the practical sense.

Similarly, our observations of $\tau$ Boo resulted in a radial-velocity variation consistent with the predicted curve computed from the latest orbital elements (private communication with Dr. R. P. Butler) with an $O-C$ deviation of $\sim 30$ m s$^{-1}$.

It should finally be remarked that the precision of measuring the radial-velocity variations described in this paper is nothing but that of a short time-scale ($\sim$ several days). In forthcoming papers we will report on the precision over a longer time-scale (months–years), with which various other factors are involved (e.g., heliocentric correction, long-term stability of the spectrograph, etc.).

We would like to express our hearty thanks to Dr. G. W. Marcy for providing us with the very high-resolution FTS spectra of the I$_2$ absorption lines upon our request, as well as to Dr. R. P. Butler for information concerning the updated orbital elements of $\tau$ Boo and $\upsilon$ And. Thanks are also due to the referee, Dr. M. Kürster, for constructive comments and suggestions which were quite helpful to improve the contents of this paper. This work is based on observations carried out within the frame work of the OAO research project “Comprehensive Spectroscopic Study of Stars with Planets”, which aims to understand the property of planet-harboring stars by analyzing stellar abundances and line profiles, as well as to improve the precision of measuring stellar radial velocities to a level of planet-detectability.

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