FOUR NEW PLANETS ORBITING SOMEWHAT METAL-ENRICHED STARS

C.G. Tinney\(^2\), R. Paul Butler\(^3\), Geoffrey W. Marcy\(^4,5\), Hugh R.A. Jones\(^6\), Alan J. Penny\(^7\), Chris McCarthy\(^3\), Brad D. Carter\(^8\), Jade Bond\(^9,2\)

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ABSTRACT

We report the detection of four new extra-solar planets from the Anglo-Australian Planet Search orbiting the somewhat metal-enriched stars HD 73526, HD 76700, HD 30177 and HD 2039. The planetary companion of HD 76700 has a circular orbit with a period of 3.98 d. With \(M\sin i=0.197\pm0.017\)M\(_{\text{JUP}}\), or 0.69 times the mass of Saturn, is one of the lowest minimum mass extra-solar planets yet detected. The remaining planets all have elliptical orbits with periods ranging from 190.5 d to 4.4 yr. All four planets have been found orbiting stars from a sub-sample of twenty metal-enriched and faint (V<9) stars, which was added to the Anglo-Australian Planet Search’s magnitude-limited V<7.5 main sample in October 1998. These stars were selected to be metal-enriched on the basis of their Strömgren photometry, and their enrichment has been subsequently confirmed by detailed spectroscopic analysis.

Subject headings: planetary systems – stars: individual (HD2039, HD73526, HD30177, HD76700)

1. INTRODUCTION

The Anglo-Australian Planet Search (AAPS) is a long-term planet detection program which aims to perform extra-solar planet detection and measurement at the highest possible precision. Together with programmes using similar techniques on the Lick 3 m and Keck I 10 m telescopes (Fischer et al. 2001; Vogt et al. 2000), it provides similar techniques on the Lick 3 m and Keck I 10 m telescopes (Fischer et al. 2001; Vogt et al. 2000), it provides the G-dwarfs in the AAPS (Bond 2002), which indicates a metallicity of [Fe/H]=+0.197. A detailed metallicity analysis has been performed for all the G-dwarfs in the AAPS (Bond 2002), which indicates a metallicity of [Fe/H]=+0.19±0.09, in agreement with the uvby-based estimate. The b−y colour of HD 30177 indicates \(T_{\text{eff}}=5320\pm20\text{K}\) (Hauck & Mermilliod 1997; Olsen

2. CHARACTERISTICS OF THE HOST STARS

HD 30177 (HIP 21850, SAO 233633) is a chromospherically inactive (log \(R'_{\text{HK}}=-5.08\); Tinney et al. (2002b)) G8V star (Houck & Cowley 1975). HD 30177 was observed 105 times by the HIPPARCOS satellite and found to be photometrically stable with a standard deviation of 0.017 magnitudes. Its HIPPARCOS parallax of 18.3±0.8 mas implies absolute magnitudes of M\(\text{V}=4.72\pm0.09\) (ESA 1997) and M\(\text{bol}=4.36\pm0.10\) (Cox 2000). Strömgren uvby photometry from the General Catalogue of Photometric Data\(^{10}\) (Hauck & Mermilliod 1997), together with the uvby calibrations of (Schuster & Nissen 1989) indicate a metallicity of [Fe/H]=+0.20±0.16. A detailed metallicity analysis has been performed for all the G-dwarfs in the AAPS (Bond 2002), which indicates a metallicity of [Fe/H]=+0.19±0.09, in agreement with the uvby-based estimate. The b−y colour of HD 30177 indicates \(T_{\text{eff}}=5320\pm20\text{K}\) (Hauck & Mermilliod 1997; Olsen

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\(^1\) Based on observations obtained at the Anglo-Australian Telescope, Siding Spring, Australia.
\(^2\) Anglo-Australian Observatory, PO Box 296, Epping, 1710. Australia. cgt@aoepp.aao.gov.au
\(^3\) Carnegie Institution of Washington, Department of Terrestrial Magnetism, 5241 Broad Branch Rd NW, Washington, DC 20015-1305
\(^4\) Department of Astronomy, University of California, Berkeley, CA 94720
\(^5\) Department of Physics and Astronomy, San Francisco State University, San Francisco, CA 94132.
\(^6\) Astrophysics Research Institute, Liverpool John Moores University, Twelve Quays House, Egerton Wharf, Birkenhead CH4 1LD, UK
\(^7\) Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, U.K.
\(^8\) Faculty of Sciences, University of Southern Queensland, Toowoomba, 4350. Australia.
\(^9\) School of Physics, University of Sydney, Sydney, 2000. Australia.
\(^10\) Data obtained directly from http://obswww.unige.ch/gcpd/gcpd.html
1984). From HD30177’s \( \log R'_{HK} = -5.08 \) we estimate intrinsic stellar velocity jitter to be in the range 2-4 m s\(^{-1}\) (Saar et al. 1998).

Figure 1 shows evolutionary tracks at \([Fe/H]=+0.2\) and +0.1 for stars of near-Solar mass from the compilation of Girardi et al. (2000). The \([Fe/H]=+0.1\) tracks were obtained by interpolation between the \([Fe/H]=+0.2\) and \([Fe/H]=0.0\) tracks in Girardi et al. (2000). Based on these models and the metallicity measurements for HD 30177, its mass is estimated to be 0.95\(\pm\)0.055 M\(_{\odot}\), and it would appear (in common with HD 73526 and HD 76706) to be beginning its evolution off the main sequence.

**HD 73526** (HIP 42282, SAO 220191) is a G6V dwarf (Houck 1978) for which no \( R'_{HK} \) estimate is currently available. It was observed 137 times by HIPPARCOS, but its relative faintness means that only a 0.02 magnitude standard deviation limit is placed on its photometric stability. Its HIPPARCOS parallax is 10.6\(\pm\)1.0 mas, which indicates \( M_V = 4.1\pm0.2\) and \( M_{bol} = 3.7\pm0.2 \) (ESA 1997; Cox 2000). As for HD 30177 (see above), Strömgren \( uvby \) photometry indicates a metallicity of \([Fe/H]=+0.10\pm0.16\) (Hauk & Mermilliod 1997; Schuster & Nissen 1989), while a detailed metallicity analysis gives \([Fe/H]=+0.11\pm0.10\) (Bond 2002). The GCPD \( b-y \) colour of HD 73526 indicates \( T_{eff} =5450\pm20\) K (Hauk & Mermilliod 1997; Olsen 1984). Based on the evolutionary tracks shown in Figure 1, HD 73526 is estimated to have a mass of 1.05\(\pm\)0.11 M\(_{\odot}\).

**HD 76700** (HIP 43686, SAO 250370, LTT 3291) is catalogued as a G6V dwarf by SIMBAD, as G5 by the Henry-Draper catalogue (Cannon & Pickering 1918-24) and as G8 by HIPPARCOS (ESA 1997). The HIPPARCOS B-V colour (+0.745) would indicate a G8 spectral type is more likely than G5 or G6, though the GCPD \( b-y \) colour (Hauk & Mermilliod 1997) would indicate a G6 type is more appropriate. No \( R'_{HK} \) estimate is available. It was observed 109 times by HIPPARCOS, which found it to have constant magnitude with a standard deviation of 0.012 magnitude. Its HIPPARCOS parallax is 16.8\(\pm\)0.7 mas, which indicates \( M_V = 4.3\pm0.1\) and \( M_{bol} = 3.9\pm0.2 \) (ESA 1997; Lang 1992). Strömgren \( uvby \) photometry indicates a metallicity of \([Fe/H]=+0.14\pm0.16\) (Hauk & Mermilliod 1997; Schuster & Nissen 1989), while a detailed metallicity analysis gives \([Fe/H]=+0.10\pm0.11\) (Bond 2002). The GCPD \( b-y \) colour indicates a \( T_{eff} = 5423\pm20\) K (Hauk & Mermilliod 1997; Olsen 1984). Based on the evolutionary tracks shown in Figure 1, HD 76700 is estimated to have a mass of 1.00\(\pm\)0.05 M\(_{\odot}\).

There is no published \( \log R'_{HK} \) measurement for HD 76700. Because the velocity amplitude observed in this star is small (26\(\pm\)2 m s\(^{-1}\)), a Ca HK spectrum was acquired to determine the level at which our results could be affected by velocity jitter. Figure 2 shows this spectrum for HD 76700 compared to those for several objects of similar spectral type, along with their spectral types and \( \log R'_{HK} \) values (Tinney et al. 2002b).

HD 76700 shows no evidence for a line reversal. Based on this comparison we assign an upper limit to the \( \log R'_{HK} \) for HD 76700 of -4.9, from which we estimate its intrinsic stellar velocity jitter to be in the range 3-6 m s\(^{-1}\) or less (Saar et al. 1998).

**HD 2039** (HIP 1931, SAO 23205) is a chromospherically active (\( R'_{HK} = -4.91 \); Tinney et al. (2002b)) star classified as G2/G3 IV/V by Houck & Cowley (1975). It was observed 147 times by HIPPARCOS, but its relative faintness means that only a 0.022 magnitude standard deviation limit is placed on its photometric stability. Its HIPPARCOS parallax is 11.1\(\pm\)1.1 mas, which indicates \( M_V = 4.25\pm0.24 \) and \( M_{bol} = 4.22\pm0.25 \) (ESA 1997; Cox 2000). There are multiple measures of this star’s Strömgren \( uvby \) photometry, the mean of which indicates a metallicity of \([Fe/H]=+0.10\pm0.16\) (Hauk & Mermilliod 1997; Schuster & Nissen 1989). A detailed metallicity analysis gives \([Fe/H]=+0.10\pm0.11\) (Bond 2002). The \( b-y \) colour of HD 2039 indicates \( T_{eff} = 5675\pm20\) K (Hauk & Mermilliod 1997; Olsen 1984). Based on the evolutionary tracks shown in Figure 1, HD 2039 is estimated to have a mass of 0.98\(\pm\)0.05 M\(_{\odot}\).

### 3. RADIAL VELOCITY OBSERVATIONS AND ORBITAL SOLUTIONS

Fifteen observations of HD 30177 are listed in Table 1. The column labelled “Uncertainty” is the velocity uncertainty produced by our least-squares fitting procedure. This fit simultaneously determines the Doppler shift and the spectrograph point-spread function (PSF) for each observation made through the iodine cell, given an iodine absorption spectrum and an “iodine free” template spectrum of the object (Butler et al. 1996). The uncertainty is derived for each measurement by taking the mean of four hundred useful spectral regions (each 2 Å long) from each exposure. This uncertainty includes the effects of photon-counting uncertainties, residual errors in the spectrograph PSF model, and variation in the underlying spectrum between the template and “iodine free” epochs. All velocities are measured relative to the zero-point defined by the template observation. Only observations where the uncertainty is less than twice the median uncertainty are listed. These data are shown in Figure 3. The figure shows the best-fit Keplerian model for the data, with the resultant orbital parameters listed in Table 2. Due to HD 30177’s faintness compared to the AAPS main sample, the residuals about the fit (14 m s\(^{-1}\)) are significantly higher than the baseline 3 m s\(^{-1}\) precision level demonstrated for the main sample (Butler et al. 2001; Jones et al. 2002a).

Eighteen observations of HD 73526 are listed in Table 3, and they are shown in Figure 4 along with a Keplerian fit to the data with the orbital parameters listed in Table 2. Note again the larger residuals (12 m s\(^{-1}\)) compared to the AAPS main sample. Twenty-four observations of HD 76700 are listed in Table 4, and they are shown in Figure 5 along with a Keplerian fit to the data with the orbital parameters listed in Table 2. The thirty-six observations of HD 2039 are listed in Table 5, and they are shown in Figure 5 along with a Keplerian fit to the data with the orbital parameters listed in Table 2.

### 4. DISCUSSION

The resultant minimum companion mass for HD 76700 is \( M \sin i = 0.197\pm0.05\) M\(_{JUP}\), with an orbital semi-major axis \( a = 0.049\pm0.04\) au and eccentricity \( e = 0.00\pm0.04 \). This zero eccentricity is consistent with the expectation that a planet with a period of just 3.971\(\pm\)0.001 d will almost certainly lie in an orbit which has been tidally...
circularised (Marcy & Butler 1998). The resulting orbital parameters for HD 76700 place it amongst the planetary companions with the lowest known minimum masses. HD 76700, joins HD 49674, HD 16141, HD 168746 & HD 46375 (Butler et al. 2002b; Marcy, Butler & Vogt 2000; Pepe et al. 2002) in the group of extra-solar planetary companions with measured minimum masses less than a Saturn mass (0.299 M_JUP).

The remaining three extra-solar planets all have elliptical orbits, though the ellipticity of the orbit for the companion to HD 30177 (\(e=0.22\pm0.17\)) is not different from zero with great significance. As further data are acquired over the coming years this parameter will become far better constrained, and it is possible that this extra-solar planet could turn out to be in a substantially circular orbit. If so this system would join with the other known nearly circular systems with gas-giant planets lying in orbits between where the Earth and Jupiter lie in our own Solar System (\(e\) Ret, HD 4208, the outer components of 47 UMa, HD 28185 (Jones et al. 2002a)). These extra-solar planets would seem to indicate that gas-giants exist in nearly circular orbits with semi-major axes all the way out to, and beyond that of Jupiter, as confirmed recently by the detection of the outer planet in the 55 Cnc system (Marcy et al. 2002a).

Of the twenty metal-enriched stars included as a subsample along with our main sample in late 1999, five have revealed the presence of planetary companions (the four planets discussed here – HD 30177, 73526, 76700 and 2039 – along with the previously known companion to HD 83443 (Butler et al. 2002a; Mayor et al. 2002)). This gives us a lower limit (there may be longer period or lower mass planets present which we cannot yet detect) to the discovery rate of 25\% for this “metallicity-biased” sub-sample. This compares with the overall discovery rates estimated for the Keck, Lick and AAPS of \(\sim8\%\) (ie \(8\%\) of stars surveyed have planets in orbits within 3.5 a.u. of their host stars (Butler et al. 2002c)) – a difference which, while not of great statistical significance, is not unexpected given that extra-solar planets seem to be being found preferentially around metal-enriched stars (eg. Reid (2002); Laughlin (2000) and references therein). It is also interesting to note (even if perhaps not statistically significant) that all four of the stars in this paper would seem to be beginning their evolution off the main sequence (see Fig 1).

These results would suggest that the biasing of planet surveys toward metal-enriched host stars may offer a benefit in the planet detection rate. However, such an increased discovery rate must be balanced against the fact that it will produce an inherently biased sample of extra-solar planets. With the total number of extra-solar planets still numbering less than a hundred, and the parameters of this ensemble of planets still poorly placed in a scheme of extra-solar planetary formation and evolution, now is not the time for planet searches to begin biasing their large surveys in the chase for better “hit rates” at the expense of scientific utility.

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Fig. 1.— Evolutionary tracks from the compilation of Girardi et al. (2000). The Zero Age Main Sequence (ZAMS) is shown as a solid line, with evolutionary models at the indicated masses shown as *dot-dashed* lines. The open circles and uncertainties indicate the stars under discussion in this paper, with their estimated uncertainties indicated in brackets. The [Fe/H]=+0.2 tracks are directly from Girardi et al. (2000), while the [Fe/H]=+0.1 tracks were obtained by interpolation between the catalogued [Fe/H]=+0.2 and 0.0 models.
Fig. 2.— UCLES spectrum in the region of the Ca H line for HD 76700 and several comparison objects with log R'\textsubscript{HK} measurements from Tinney et al. (2002b). For each object the spectral type and measured log R'\textsubscript{HK} value is shown. Based on these we assign an upper limit to the log R'\textsubscript{HK} value for HD 76700 of -4.9.

Fig. 3.— AAT Doppler velocities for HD 30177 from 1998 November to 2002 May. The solid line is a best fit Keplerian with the parameters shown in Table 2. The rms of the velocities about the fit is 14 m s\textsuperscript{-1}. Assuming 0.95 M\textsubscript{\odot} for the primary, the minimum (M\textsubscript{sin i}) mass of the companion is 7.7 ± 1.5 M\textsubscript{Jup}, and the semi-major axis is 2.6 ± 0.9 a.u.
**Fig. 4.** — AAT Doppler velocities for HD 73526 from 1999 January to 2002 June. The solid line is a best fit Keplerian with the parameters shown in Table 2. The rms of the velocities about the fit is $18 \text{ m s}^{-1}$. Assuming $1.05 \, M_\odot$ for the primary, the minimum $(M \sin i)$ mass of the companion is $3.0 \pm 0.3 \, M_{\text{JUP}}$, and the semi-major axis is $0.66 \pm 0.05 \, \text{a.u.}$

**Fig. 5.** — AAT Doppler velocities for HD 76700 from 1999 February to 2002 June, phased at the best fit Keplerian period of $3.971 \, \text{d}$ (left panel) and plotted unphased from the last three observing runs in 2002 (right panel). The plotted Keplerian has the parameters shown in Table 2. The rms of the velocities about the fit is $6.2 \, \text{m s}^{-1}$. Assuming $1.0 \, M_\odot$ for the primary, the minimum $(M \sin i)$ mass of the companion is $0.197 \pm 0.017 \, M_{\text{JUP}}$, and the semi-major axis is $0.049 \pm 0.004 \, \text{a.u.}$

**Fig. 6.** — AAT Doppler velocities for HD 2039 from 1998 November to 2002 June, with the best fit Keplerian with parameters shown in Table 2. The rms of the velocities about the fit is $15 \, \text{m s}^{-1}$. Assuming $0.98 \, M_\odot$ for the primary, the minimum $(M \sin i)$ mass of the companion is $5.1 \pm 1.7 \, M_{\text{JUP}}$, and the semi-major axis is $2.2 \pm 0.2 \, \text{a.u.}$
| JD$^a$ (-2451000) | RV$^a$ (m s$^{-1}$) | Uncertainty (m s$^{-1}$) |
|------------------|------------------|------------------|
| 118.0974         | 77.9             | 10.9             |
| 119.1924         | 37.2             | 17.1             |
| 121.1514         | 49.7             | 14.8             |
| 157.1022         | 95.4             | 8.6              |
| 211.9834         | 92.4             | 11.3             |
| 212.9660         | 92.5             | 10.4             |
| 213.9995         | 92.3             | 9.1              |
| 214.9506         | 104.0            | 9.3              |
| 525.9973         | 26.9             | 6.9              |
| 630.9156         | -0.5             | 9.9              |
| 768.3296         | -61.5            | 10.2             |
| 921.1075         | -117.8           | 10.2             |
| 1127.3205        | -168.5           | 12.4             |
| 1188.2532        | -172.9           | 7.8              |
| 1358.9181        | -173.4           | 7.8              |

$^a$Julian Dates (JD) are barycentric. Radial Velocities (RV) are barycentric, but have an arbitrary zero-point determined by the radial velocity of the template, as described in Section 3.
Table 2

Orbital Parameters

| Parameter                  | HD 30177   | HD 73526   | HD 76700   | HD 2039   |
|---------------------------|------------|------------|------------|------------|
| Orbital period $P$ (d)    | 1620±800   | 190.5±3.0  | 3.971±0.001| 1190±150   |
| Velocity amp. $K$ (m s$^{-1}$) | 140±10     | 108±8      | 25±2       | 136±30     |
| Eccentricity $e$          | 0.22±0.17  | 0.34±0.08  | 0.00±0.04  | 0.69±0.15  |
| $\omega$ ($^\circ$)      | 288±40     | 207±30     | -          | 333±20     |
| $a_1 \sin i$ (km)         | (3.0±1.5)$\times10^6$ | (0.265±0.01)$\times10^6$ | 1381±1.2  | (1.61±0.45)$\times10^6$ |
| Periastron Time (JD-245000) | 1027±200   | 951±12     | 1212.9±0.1 | 836±150    |
| $M \sin i$ (M$\text{JUP}$) | 7.7±1.5    | 3.0±0.3    | 0.197±0.017| 5.1±1.7    |
| $a$ (AU)                  | 2.6±0.9    | 0.66±0.05  | 0.049±0.004| 2.2±0.2    |
| RMS about fit (m s$^{-1}$) | 14          | 18          | 6.2        | 15         |

Table 3

Velocities for HD 73526

| JD$^a$ (-2451000) | RV$^a$ (m s$^{-1}$) | Uncertainty (m s$^{-1}$) |
|-------------------|---------------------|--------------------------|
| 212.1302          | 23.5                | 12.9                     |
| 213.1314          | 66.8                | 13.7                     |
| 214.2389          | 61.6                | 14.9                     |
| 236.1465          | 48.4                | 10.9                     |
| 630.0280          | 35.5                | 11.0                     |
| 717.9000          | -120.7              | 12.8                     |
| 920.1419          | -32.0               | 13.4                     |
| 984.0378          | 78.0                | 9.3                      |
| 1009.0976         | 71.8                | 9.7                      |
| 1060.8844         | -58.9               | 7.4                      |
| 1091.8465         | -149.8              | 13.6                     |
| 1386.9003         | 51.8                | 6.8                      |
| 1387.8921         | 64.0                | 6.2                      |
| 1420.9248         | -14.4               | 7.8                      |
| 1421.9199         | -9.6                | 6.5                      |
| 1422.8602         | -9.8                | 7.3                      |
| 1424.9237         | -19.1               | 10.4                     |
| 1454.8529         | -109.0              | 6.3                      |

$^a$As for Table 1
Table 4

Velocities for HD 76700

| JD$^a$ (-2451000) | RV$^a$ (m s$^{-1}$) | Uncertainty (m s$^{-1}$) |
|------------------|---------------------|--------------------------|
| 212.1565         | 9.2                 | 6.7                      |
| 213.1501         | 40.3                | 7.6                      |
| 214.2583         | -21.3               | 8.2                      |
| 274.0177         | -18.6               | 7.9                      |
| 530.1791         | 26.7                | 8.8                      |
| 683.8938         | -19.8               | 5.7                      |
| 920.1606         | 29.7                | 7.6                      |
| 984.0068         | 22.8                | 7.1                      |
| 1009.0638        | -26.8               | 7.5                      |
| 1060.9036        | -24.3               | 4.7                      |
| 1091.8517        | -16.8               | 7.4                      |
| 1129.8425        | 18.2                | 6.7                      |
| 1359.0760        | -14.3               | 6.6                      |
| 1386.9145        | -20.0               | 3.8                      |
| 1387.9170        | 23.2                | 3.9                      |
| 1388.9898        | 16.5                | 3.4                      |
| 1389.8741        | -11.8               | 3.9                      |
| 1420.9418        | 7.3                 | 4.5                      |
| 1421.9331        | -19.3               | 3.1                      |
| 1422.8793        | -11.0               | 2.7                      |
| 1424.9439        | 0.6                 | 5.3                      |
| 1452.8943        | -4.2                | 3.8                      |
| 1454.8682        | -3.2                | 3.9                      |
| 1455.8565        | 22.8                | 3.1                      |

$^a$As for Table 1
Table 5

Velocities for HD 2039

| JD$^a$ (-2451000) | RV$^a$ (m s$^{-1}$) | Uncertainty (m s$^{-1}$) |
|-------------------|---------------------|--------------------------|
| 118.0578          | 24.0                | 8.4                      |
| 118.9610          | -23.8               | 16.9                     |
| 119.9445          | 0.0                 | 11.5                     |
| 121.0385          | -33.0               | 16.1                     |
| 211.9514          | -10.1               | 18.7                     |
| 212.9234          | 3.9                 | 13.3                     |
| 213.9749          | -3.9                | 17.0                     |
| 214.9171          | -14.1               | 13.2                     |
| 386.3227          | -54.7               | 17.1                     |
| 387.2981          | -33.2               | 15.3                     |
| 411.2293          | -14.2               | 15.6                     |
| 414.2585          | -16.5               | 10.6                     |
| 473.0883          | -42.5               | 10.6                     |
| 525.9286          | -78.7               | 13.9                     |
| 527.9226          | -28.9               | 11.0                     |
| 745.2702          | -51.8               | 17.4                     |
| 828.0703          | -43.1               | 12.5                     |
| 828.9944          | -49.3               | 10.4                     |
| 829.9757          | -45.1               | 11.7                     |
| 856.0702          | -33.5               | 14.6                     |
| 919.9434          | -25.7               | 14.7                     |
| 920.9672          | -22.5               | 14.5                     |
| 1093.2947         | 136.2               | 14.4                     |
| 1127.2341         | 98.9                | 15.1                     |
| 1151.2230         | 65.7                | 8.4                      |
| 1152.0860         | 66.4                | 9.2                      |
| 1154.2124         | 74.6                | 11.4                     |
| 1187.0957         | 55.1                | 9.7                      |
| 1188.0300         | 48.7                | 8.4                      |
| 1189.1502         | 58.6                | 11.6                     |
| 1190.0932         | 48.5                | 8.4                      |
| 1422.3281         | -9.7                | 11.2                     |
| 1425.3322         | -3.2                | 7.7                      |
| 1455.2853         | -29.4               | 6.1                      |

$^a$As for Table 1