The HARPS search for southern extra-solar planets *

XIV. Gl 176b, a super-Earth rather than a Neptune, and at a different period

T. Forveille$^1$, X. Bonfils$^{2,1,3}$, X. Delfosse$^1$, M. Gillon$^4$, S. Udry$^4$, F. Bouchy$^5$, C. Lovis$^4$, M. Mayor$^4$, F. Pepe$^4$, C. Perrier$^1$, D. Queloz$^2$, N. Santos$^5$, and J.-L. Bertaux$^6$

1 Laboratoire d’Astrophysique de Grenoble, Observatoire de Grenoble, Université Joseph Fourier, CNRS, UMR 571 Grenoble, France
2 Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
3 Centro de Astronomia e Astrofísica da Universidade de Lisboa, Observatório Astronómico de Lisboa, Tapada da Ajuda, 1349-018 Lisboa, Portugal
4 Observatoire de Genève, Université de Genève, 51 ch. des Maillettes, 1290 Sauveney, Switzerland
5 Institut d’Astrophysique de Paris, CNRS, Université Pierre et Marie Curie, 98bis Bd Arago, 75014 Paris, France
6 Service d’Aéronomie du CNRS, BP 3, 91371 Verrières-le-Buisson, France

ABSTRACT

Context. A 10.24 days Neptune-mass planet was recently announced to orbit the nearby M2 dwarf Gl 176, based on 28 radial velocities measured with the HRS spectrograph on the Hobby-Heberly Telescope.

Aims. We obtained 57 radial velocities of Gl 176 with the ESO 3.6m telescope and the HARPS spectrograph, which is known for its sub-m/s stability. The median photon-noise standard error of our measurements is 1.1 m/s, significantly lower than the 4.7 m/s of the HET velocities, and the 4 years period over which they were obtained has much overlap with the epochs of the HET measurements.

Methods. The HARPS measurements show no evidence for a signal at the period of the putative HET planet, suggesting that its detection was spurious. We do find, on the other hand, strong evidence for a lower mass 8.4 $M_{\text{Earth}}$ planet, in a circular-orbit and at the different period of 8.78 days. The host star has moderate magnetic activity and rotates on a 39-days period, which we confirm through modulation of both contemporaneous photometry and chromospheric indices. We detect that period as well in the radial velocities, but it is well removed from the orbital period and so we can exclude confusion.

Results. This new detection of a super-Earth ($2 M_{\text{Earth}} < M \sin(i) < 10 M_{\text{Earth}}$) around an M dwarf adds to the growing evidence that such planets are common around very low mass stars: a third of the 20 known planets with $M \sin(i)$ orbital a 39-days period, which we confirm through modulation of both contemporaneous photometry and chromospheric indices. We detect that period as well in the radial velocities, but it is well removed from the orbital period and so we can exclude confusion.

Conclusions. This new detection of a super-Earth ($2 M_{\text{Earth}} < M \sin(i) < 10 M_{\text{Earth}}$) around an M dwarf adds to the growing evidence that such planets are common around very low mass stars: a third of the 20 known planets with $M \sin(i)$ orbital a 39-days period, which we confirm through modulation of both contemporaneous photometry and chromospheric indices. We detect that period as well in the radial velocities, but it is well removed from the orbital period and so we can exclude confusion.

Key words. Stars: individual: Gl 176 – Stars: planetary systems – Stars: late-type – Techniques: radial-velocity

1. Introduction

Of the ~250 planetary systems currently known from radial velocity monitoring, just half a dozen are centered around M dwarfs ($M < 0.6 M_\odot$). This in part reflects a selection bias, since an order of magnitude fewer faint M dwarfs are searched for planets than brighter solar-type stars are, but M dwarfs also seem to genuinely have fewer massive planets ($\sim M_{\text{Earth}}$) than the more massive solar-type stars do (Bonfils et al. 2006, Johnson et al. 2007). They seem on the other hand (Bonfils et al. 2006) to have larger numbers of the harder to detect Neptune-mass and super-Earth planets: a third of the ~20 planets with $M \sin(i) < 0.1 M_{\text{Earth}}$ known to date orbit an M dwarf, in spite of solar-type stars outnumbering those by an order of magnitude in planet search samples. As a consequence of their small overall number, each individual M-dwarf planetary system still plays a significant role in defining these emerging statistical properties.

Very recently, Endl et al. (2008) announced the discovery of a planet with a minimum mass of $M \sin(i) = 25 M_{\text{Earth}}$ in a 10.24 days orbit around a nearby M2.5 dwarf, Gl 176 (also HD 285968, HIP 21932, LHS 196) is a $V=9.97$ (Upgren 1974) member of the immediate solar neighborhood ($\text{par}=106.2\pm2.5$ mas, $d = 9.4$ pc, Perryman & ESA 1997). The 2MASS photometry (Skrutskie et al. 2006) and the parallax result in an absolute magnitude of $M_K = 5.74$, and together with the K-band mass-luminosity relation of Delfosse et al. (2000) in a mass of 0.50 $M_\odot$. Based on the Bonfils et al. (2005) photometric metallicity calibration, $[\text{Fe/H}]$ is $-0.1\pm0.2$ and therefore solar within its uncertainty.

We have independently been monitoring the radial velocity of Gl 176 using the HARPS spectrograph on the ESO 3.6m telescope, over a period which largely overlaps the epochs of the Endl et al. (2008) observations. Section 2. describes those independent measurements and concludes that they do not confirm the 10.24 days planet. Section 3. takes a closer look at those measurements and finds that they contain two coherent signals, with periods of 8.78 and 40.0 days. Section 4 discusses differential photometry and variation of chromospheric indices, to conclude that the 40 days signal reflects the stellar rotation period. The 8.78 days period on the other hand is due to a bona-fide
planet, with a minimum mass of only 8.4 $M_{\text{Earth}}$. Section 5 concludes with a brief discussion of the new planet.

2. HARPS Doppler measurements and orbital analysis

We observed Gl 176 with HARPS (High Accuracy Radial velocity Planet Searcher) as part of the guaranteed-time program of the instrument consortium. HARPS is a high-resolution (R = 115 000) fiber-fed echelle spectrograph, optimised for planet search programmes and asteroseismology. It is the most precise spectro-velocimeter to date, with a long-term instrumental drifts < 1 m s$^{-1}$. Most M dwarfs are too faint for us to reach the stability limit of HARPS within realistic integration times, and dispensing with the simultaneous thorium light produces much cleaner stellar spectra, suitable for quantitative spectroscopic analyses.

For the $V = 9.97$ Gl 176 we use 15 mn exposures, and the median S/N ratio of our 57 spectra is 60 per pixel at 550 nm. The radial velocities (Table 1) only available electronically) were obtained with the standard HARPS reduction pipeline, based on cross-correlation with a stellar mask and a precise nightly wavelength calibration from ThAr spectra (Lovis & Pepe 2007). They have a median internal error of only 1.1 m s$^{-1}$, which includes both the nightly zero-point calibration uncertainty (≈ 0.5 m s$^{-1}$) and the photon noise, computed from the full Doppler information content of the spectra (Bouchy et al. 2001).

Table 1. Observed and inferred stellar parameters for Gl 176

| Parameter | Gl 176 |
|-----------|--------|
| Spectral Type | M2V |
| V | 9.97 ± 0.03 |
| $\pi$ | 10.16 ± 2.51 |
| Distance | 10.10 ± 0.06 |
| $r_{\text{K}}$ | 5.607 ± 0.034 |
| $M_{\text{K}}$ | 5.74 ± 0.06 |
| $L_*/L_{\odot}$ | 0.022 |
| $v \sin i$ | $3.5 \times 10^{-5}$ |
| $[Fe/H]$ | $-0.1 \pm 0.2$ |
| $M_{\ast}$ | 0.50 |

The computed velocities exhibit an rms dispersion of 5.3 m s$^{-1}$. This is much above the 1 m s$^{-1}$ internal errors and significantly more than we observe for stars with similar chromospheric activity, but less than the $\sim 8$ m s$^{-1}$ expected from the 11.7 m s$^{-1}$ velocity amplitude of the Endl et al. (2008) orbit. Fig. 1 confirms that the HARPS velocities are more tightly packed than both the HET measurements (top panel) and the predictions of the Endl et al. (2008) orbit (lower panel). Its lower panel demonstrates that they do not phase on the Endl et al. (2008) period, and we verified that the subset of the HARPS dataset which overlaps the published HET measurements does not either. Since any instrumental or astrophysical noise can only increase the velocity dispersion, never decrease it, the HARPS measurements set a $\sim 7.5$ m s$^{-1}$ ceiling on the radial velocity amplitude of a Keplerian orbit (except for unrealistically high eccentricities). This forces us to conclude that the Endl et al. (2008) orbit must be spurious, though we do not have a ready explanation for why.

![Fig. 1. Top panel: HARPS (red filled symbols) and Endl et al. (2008) (blue empty symbols) radial velocities of Gl 176 as a function of time, overlaid with the prediction of the Endl et al. (2008) orbit. Bottom panel: HARPS radial velocities phased at the 10.24 days period of the Endl et al. (2008) orbit, overlaid with the radial velocity prediction for that orbit.](image1)

![Fig. 2. Lomb-Scargle periodogram of the raw HARPS radial velocities (top panel), and of the velocities after subtraction of the 40-day signal (bottom panel).](image2)
Table 2. Orbital elements for the two-keplerian orbital model of Gl 176.

| Element | Value | Standard error |
|---------|-------|----------------|
| γ       | 26.4105 km/s | 0.0004 |
| P_1 [days] | 8.7836 | 0.0054 |
| e_1 | 0.0 | Fixed |
| om_1 [deg.] | 0.0 | Fixed |
| T0_1 [jdb] | 2454399.79 | 0.33 |
| K1_1 [m/s] | 4.12 | 0.52 |
| P_2 [days] | 40.00 | 0.11 |
| e_2 | 0.0 | Fixed |
| om_2 [deg.] | 0.0 | Fixed |
| T0_2 [jdb] | 2454291.07 | 1.31 |
| K1_2 [m/s] | 4.23 | 0.53 |

3. Orbital analysis

Our radial velocity measurements do show coherent structure, and a Lomb-Scargle periodogram (Press et al. 1992) shows two narrow peaks around 8.8 and 40 days (Fig. 2 top panel). The two peaks have similar false alarm probabilities of 0.1%, and their spacing is well removed from any significant feature in the window function. We therefore analysed them simultaneously and searched for 2-planet Keplerian solutions with Stakanof (Tamuz, in prep.), a program which uses genetic algorithms to efficiently explore the large parameter space of multi-planet models. Stakanof robustly converged to a 2-keplerian solution with periods which match the two periodogram peaks. Subtracting the longer period signal from the velocities increases the significance of the 8.8 day period in the periodogram (Fig. 2 lower panel), further increasing our confidence that this signal is real. Subtracting the short period signal, on the other hand, produces a periodogram (not shown) with a less convincing 40 days peak.

The 2-planet model describes our measurements well, but certainly not perfectly (σ = 2.5 m s⁻¹, √2 = 2.46 per degree of freedom). A Lomb-Scargle periodogram of the residuals of this 2-planet solution however shows no significant peak, and the significant residuals therefore contain no immediate evidence for an additional component.

Both Keplerian signals have amplitudes of ~4 m s⁻¹, which with hindsight is well under the sensitivity limit of Endl et al. (2008). Neither of their eccentricities is significant, and we therefore adopt circular orbits as our preferred solution (Table 2, Fig. 3); that choice does not affect any of our conclusions. The inner and outer planets, in a Keplerian interpretation of the radial velocity variations, have minimum masses (m sin i) of 8 and 14 M_\text{Earth} and projected semi-major axes of 0.066 and 0.18 AU.

4. Activity analysis

Apparent Doppler shifts unfortunately do not always originate in the gravitational pull of a companion, because stellar surface inhomogeneities, such as plages and spots, can break the balance between light emitted in the red-shifted and the blue-shifted parts of a rotating star. These inhomogeneities then translate into rotationally modulated changes of both the shape and the centroid of spectral lines (e.g. Saar & Donahue 1997, Queloz et al. 2001). The activity level of Gl 176 is similar to that of Gl 674 (Fig. 4), where a spot is responsible for a 5 m s⁻¹ radial velocity signal (Bonfils et al. 2007).

For well resolved rotational broadenings, correlated variation in the shape, parametrized by the line bisector, and in the centroid, provide an excellent diagnostic of such apparent velocity variations. We however measure from our Gl 176 spectra a rotational velocity of v sin i < 0.8 km s⁻¹. This small rotation velocity removes much of the usual power of the bisector test, since the bisector span scales with a much higher power of v sin i than the centroid (Saar & Donahue 1997, Bonfils et al. 2007).

Spots fortunately also produce flux variations, and they typically impact spectral indices, whether designed to probe the chromosphere (to which photospheric spots have strong magnetic connections), or the photosphere (because spots have cooler spectra). We therefore investigated the magnetic activity...
of Gl 176 through photometric observations (§4.1) and detailed examination of the chromospheric features in the clean HARPS spectra (§4.3).

4.1. Photometric variability

We obtained photometric measurements with the EulerCAM CCD camera of the Euler Telescope (La Silla) during 21 nights between November 10th 2007 and January 11th 2008. October Gl 176 was observed through an 1 filter, to maximize the flux of both Gl 176 and a M star in the 11.7 field of view which we planned to use as photometric reference. That planned reference however proved variable, and we had to fall back to the average of two fainter blue stars, with a summed flux of only 7% of that of Gl 176. In retrospect, this filter choice was therefore suboptimal. To minimize atmospheric scintillation noise we took advantage of the low stellar density to defocus the images to FWHM ∼ 8″, so that we could use longer exposure times. The increased read-out and sky background noises from the larger synthetic aperture which we had to use remain negligible compared to both stellar photon noise and scintillation.

We gathered 5 to 7 images per night with a median exposure time of 31 seconds, except on December 29th when we obtained sets of 5 images at three well spaced airmasses to measure the differential photometry. We tuned the parameters of the IRAF DAOPHOT package (Stetson 1987) and optimised the set of reference stars to minimise the average dispersion in the Gl 176 photometry within the individual nights. These parameters were then fixed for the analysis of the full data set. The nightly light curves for Gl 176 were normalized by that of the sum of the references, clipped at 3σ to remove a small number of outliers, and averaged to one measurement per night to examine the long term photometric variability of Gl 176. Gl 176 clearly varies with a ∼1.3% peak-to-peak amplitude, and a 40-50 days (quasi-)period (Fig. 5). To verify that this variability does not actually originate in one of the reference stars, we repeated the analysis using each of the two reference stars. Those alternate light curves are very similar to Fig. 5. The variations are fully consistent with the 38.92 days period identified by Kiraga & Stepień (2007) in a much longer photometric timeseries. Our photometry demonstrates that Gl 176, which Kiraga & Stepień (2007) find did not significantly vary until JD=2453300, has remained strongly spotted until the end of our radial velocity measurements. Our dense sampling also excludes that 38.92 days would have been an alias of the true period. We adopt the better defined Kiraga & Stepień (2007) value as the rotation period of Gl 176.

Our photometric observations are consistent with the signal of a single spot, within the limitations of their incomplete phase coverage: the variations are approximately sinusoidal, and their ∼0.2-0.3 phase shift from the corresponding radial velocity signal closely matches the difference expected for a spot. The spot would cover 2.6% of the stellar surface if completely dark, corresponding to a ∼0.16R∗ radius for a circular spot.

4.2. Variability of the spectroscopic indices

The emission reversal in the core of the Ca II H&K resonant lines and in the Hα line results from non-radiative heating of the chromosphere, which is magnetically coupled to the photospheric spots and plages. We measured in the HARPS spectra the spectral indices defined by Bonfils et al. (2007) to probe these chromospheric spectral features, and examine here their variability.

The power spectra for both the H+K and Hα indices have clear peaks near 40 days (Fig. 6 lower right panel). Within the combined uncertainties, these peaks are consistent with both the photometric period and the longer radial velocity period. The phasing of the chromospheric index and the photometry is such that lower photometric flux matches higher Ca II emission, as expected if active chromospheric regions hover above dark photospheric spots.

Though certainly not as clearly as for Gl 674 (Bonfils et al. 2007), a plot of the (apparent) radial-velocity (after subtraction of the 8.8-day period) against the H+K spectral index (Fig. 6 upper panel) similarly suggests the loop pattern which is expected for a spot (Bonfils et al. 2007): a spot produces maximal velocity offsets when it is on either edge of the star, where geometric projection reduces the apparent area of its associated chromospheric emission to an intermediate value; it produces no velocity offset when it crosses the sub-observer meridian, with a maximal projected area for a front-facing crossing and a minimal (null for a non-polar spot) projected area for a back facing crossing. The radial velocity offset therefore cancels for both the minimum and the maximumchromospheric emission, and is maximal for intermediate chromospheric emission levels. The pattern here is definitely noisier than observed on Gl 674, suggesting that the spot pattern may evolve on a time scale of the order of our observing period.
Fig. 6. Upper panel: Differential radial velocity of Gl 176, corrected for the signature of the 8.8 days planet in our 2-planet fit, as a function of the Hα (red filled circles) and Ca II H+K (green filled squares) spectral indices defined in the text for the 2007/2008 observing season. Bottom right panels: the Ca II H+K and Hα indexes phased to the longer period of the 2-planet model. Bottom left panels: Power Density spectra of the spectroscopic indices. A clear power excess peaks at 40 days (vertical dashed lines).

4.3. Planets vs. activity

In §3 we showed that our 57 radial-velocity measurements of Gl 176 are well described by two Keplerian signals. Section 4 however demonstrates that the rotation period of Gl 176 coincides with the longer of these two Keplerian periods. The stellar flux and the Ca II H+K emission vary with that period, with a phase relative to the velocity variations consistent with a magnetic spot on the stellar surface. As a consequence, some, and probably all, of the 40-day radial-velocity signal must originate in the spot. Planet-induced activity through magnetic coupling (e.g. Shkolnik et al. 2005) would in principle be an alternative explanation of the correlation, but has never been observed for such a long-period planet. The inner planet in addition is not very much less massive than the hypothetical 40-day planet. One would, at least naively, expect its position in the inner magnetosphere of Gl 176 to make up for its lower mass. The 8.8-day period however is only seen in the radial velocity signal, and it has no photometric or chromospheric counterpart.

5. Discussion and conclusions

The most important result of the above analysis is that a $M \sin(i)=8.4 \, M_{\text{Earth}}$ planet orbits Gl 176 in a $\sim 8.8$-day orbit. Variability identifies the stellar rotation period as 38.92 days, and the 8.8-day period therefore cannot reflect rotation modulation. The short period signal, in spite of its similar amplitude, also has no counterpart in either photometry or chromospheric emission, further excluding a signal caused by magnetic activity.

Like Gl 674 (Bonfils et al. 2007), Gl 176 demonstrates that single planets can be identified around moderately active M-dwarfs, at the cost of doubling or tripling the number of measurements over a magnetically quiet M-dwarf. Since the Keplerian model does not reflect a physical reality for the 40-day period, its residuals must be interpreted with caution. They are well above the measurement errors ($\bar{\chi}^2=5.86$ per degree of freedom), and could in principle reflect additional planet(s) in the system. More likely, much of these residuals stem from long term evolution of the spot pattern of Gl 176. Many additional radial velocity measurements would be needed to firmly identify additional planets amongst this spot-evolution noise. That cost may, in practice if not in theory, effectively impede the detection of multi-planet systems around moderately active stars. It may therefore not be fully by coincidence that Gl 674 and Gl 176 are both the most active M-dwarfs with known planets.

At 0.066 AU from its parent star, the thermal equilibrium temperature of Gl 176 b is $\sim 450$ K. Its $8.4 \, M_{\text{Earth}}$ mass might be sufficient for accretion of a significant gas envelope to have occurred, in particular in case the inclination would turn out to be non-trivial, but the rocky core most likely dominate the total mass (e.g. Seager et al. 2007; Valencia et al. 2007).

With a mass of only $M \sin(i)=8.4 \, M_{\text{Earth}}$, Gl 176b adds to the growing evidence (e.g. Bonfils et al. 2007) that super-Earths are...
common around very low mass stars: 6 of the 20 known planets with $M \sin(i) < 0.1 M_{\text{Jup}}$ orbit an M dwarf, in contrast to just 3 of the ~250 known Jupiter-mass planets.

Acknowledgements. We would like to thank the ESO La Silla staff for their excellent support and our collaborators of the HARPS consortium for making this instrument such a success, as well as for contributing some of the observations. Financial support from the “Programme National de Planétologie” (PNP) of CNRS/INSU, France, is gratefully acknowledged. XB acknowledge support from the Fundação para a Ciência e a Tecnologia (Portugal) in the form of a fellowship (reference SFRH/BPD/21710/2005) and a program (reference PTDC/CET/AST/72685/2006), as well as the Gulbenkian Foundation for funding through the “Programa de Estímulo Investigação”. N.C.S. would like to thank the support from Fundação para a Ciência e a Tecnologia, Portugal, in the form of a grant (references POCI/CET/AST/56453/2004 and PPCDT/CET/AST/56453/2004), and through programme Ciência 2007 (C2007-CAUP-FCT/136/2006).

References

Bonfils, X., Delfosse, X., Udry, S., Forveille, T., & Naef, D. 2006, in Tenth Anniversary of 51 Peg-b: Status of and prospects for hot Jupiter studies, ed. L. Arnold, F. Bouchy, & C. Moutou, 111–118
Bonfils, X., Delfosse, X., Udry, S., et al. 2005, A&A, 442, 635
Bonfils, X., Mayor, M., Delfosse, X., et al. 2007, A&A, 474, 293
Bouchy, F., Pepe, F., & Queloz, D. 2001, A&A, 374, 733
Delfosse, X., Forveille, T., Ségransan, D., et al. 2000, A&A, 364, 217
Endl, M., Cochran, W. D., Wittenmyer, R. A., & Boss, A. P. 2008, ApJ, 673, 1165
Johnson, J. A., Butler, R. P., Marcy, G. W., et al. 2007, ApJ, 670, 833
Kiraga, M. & Stepien, K. 2007, ArXiv e-prints, 707
Lovis, C., Mayor, M., Bouchy, F., et al. 2005, A&A, 437, 1121
Lovis, C. & Pepe, F. 2007, A&A, 468, 1115
Mayor, M., Pepe, F., Queloz, D., et al. 2003, The Messenger, 114, 20
Perryman, M. A. C. & ESA, eds. 1997, ESA Special Publication, vol. 1200, The HIPPARCOS and TYCHO catalogues, Astrometric and photometric star catalogues derived from the ESA HIPPARCOS Space Astrometry Mission
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical recipes in FORTRAN. The art of scientific computing (Cambridge University Press, —c1992, 2nd ed.)
Queloz, D., Henry, G. W., Sivan, J. P, et al. 2001, A&A, 379, 279
Saar, S. H. & Donahue, R. A. 1997, ApJ, 485, 319
Santos, N. C., Bouchy, F., Mayor, M., et al. 2004, A&A, 426, L19
Seager, S., Kuchner, M., Hier-Majumder, C. A., & Militzer, B. 2007, ApJ, 669, 1279
Shkolnik, E., Walker, G. A. H., Bohlender, D. A., Gu, P.-G., & Kürster, M. 2005, ApJ, 622, 1075
Skrutskie, M. F., Cutri, R. M., Stiening, R., & et al. 2006, AJ, 131, 1163
Stetson, P. B. 1987, PASP, 99, 191
Upgren, A. R. 1974, PASP, 86, 294
Valencia, D., Sasselow, D. D., & O’Connell, R. J. 2007, ApJ, 656, 545

List of Objects

‘Gl 176’ on page 4
‘Gl 176’ on page 4
‘Gl 176’ on page 4
‘Gl 176’ on page 4
‘Gl 176’ on page 4
‘Gl 674’ on page 4
‘Gl 176’ on page 4
‘Gl 176’ on page 4
‘Gl 581’ on page 4
‘Gl 581’ on page 4
‘Gl 674’ on page 4
‘Gl 176’ on page 4
‘Gl 176’ on page 4
‘Gl 674’ on page 4
‘Gl 176’ on page 4
‘Gl 176’ on page 4
‘Gl 176’ on page 4
Table 3. Radial-velocity measurements and error bars for Gl 176. All values are relative to the solar system barycenter, and corrected from the small perspective acceleration using the Hipparcos parallax and proper motion. Only available electronically.

| JD-2400000 | RV [km s\(^{-1}\)] | Uncertainty [km s\(^{-1}\)] |
|------------|-----------------|-----------------|
| 52986.713028 | 26.4097          | 0.0024          |
| 53336.797232 | 26.4133          | 0.0018          |
| 53367.703446 | 26.4080          | 0.0010          |
| 53371.679444 | 26.4146          | 0.0012          |
| 53372.672289 | 26.4150          | 0.0011          |
| 53373.698683 | 26.4149          | 0.0016          |
| 53375.708263 | 26.4074          | 0.0011          |
| 53376.644426 | 26.4074          | 0.0011          |
| 53377.637888 | 26.4072          | 0.0010          |
| 53378.667446 | 26.4114          | 0.0013          |
| 53674.790011 | 26.4012          | 0.0010          |
| 53693.724506 | 26.4120          | 0.0011          |
| 53695.679077 | 26.4167          | 0.0009          |
| 53697.762057 | 26.4217          | 0.0016          |
| 53699.629044 | 26.4154          | 0.0011          |
| 53721.725478 | 26.4120          | 0.0014          |
| 53725.600014 | 26.4082          | 0.0014          |
| 53727.617518 | 26.4069          | 0.0012          |
| 53784.533236 | 26.4056          | 0.0011          |
| 53786.526663 | 26.4068          | 0.0010          |
| 53809.529447 | 26.4176          | 0.0011          |
| 53810.515057 | 26.4184          | 0.0010          |
| 53811.510284 | 26.4211          | 0.0011          |
| 53812.506114 | 26.4200          | 0.0013          |
| 53813.507893 | 26.4148          | 0.0011          |
| 53814.507265 | 26.4123          | 0.0011          |
| 53815.501823 | 26.4106          | 0.0012          |
| 53817.502490 | 26.4110          | 0.0010          |
| 54048.826783 | 26.4184          | 0.0010          |
| 54050.768921 | 26.4114          | 0.0009          |
| 54052.748970 | 26.4067          | 0.0011          |
| 54054.812777 | 26.4093          | 0.0010          |
| 54078.698716 | 26.4005          | 0.0009          |
| 54080.713033 | 26.4065          | 0.0012          |
| 54082.712795 | 26.4123          | 0.0012          |
| 54084.737341 | 26.4136          | 0.0014          |
| 54114.597344 | 26.4051          | 0.0014          |
| 54117.631291 | 26.4122          | 0.0010          |
| 54122.584109 | 26.4097          | 0.0010          |
| 54135.548955 | 26.4141          | 0.0010          |
| 54140.552388 | 26.4040          | 0.0010          |
| 54142.585254 | 26.4095          | 0.0010          |
| 54166.508802 | 26.4099          | 0.0011          |
| 54168.505999 | 26.4141          | 0.0010          |
| 54170.501820 | 26.4194          | 0.0011          |
| 54174.499424 | 26.4092          | 0.0012          |
| 54342.888384 | 26.4068          | 0.0011          |
| 54345.866037 | 26.4087          | 0.0010          |
| 54385.842984 | 26.3989          | 0.0013          |
| 54386.803603 | 26.4015          | 0.0015          |
| 54387.840396 | 26.4044          | 0.0012          |
| 54390.838236 | 26.4087          | 0.0012          |
| 54392.803574 | 26.4030          | 0.0011          |
| 54393.820127 | 26.4044          | 0.0011          |
| 54394.817280 | 26.4029          | 0.0012          |
| 54423.730978 | 26.4045          | 0.0013          |
| 54428.729841 | 26.4096          | 0.0010          |