New HARPS and FEROS observations of GJ1046.

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INTRODUCTION

GJ1046 is a M2.5 V, V=11.62 mag star reported to host a substellar companion with a minimum mass in the brown dwarf mass regime (Kürster et al. 2008). The system is peculiar because of the short orbital period of only ~169 days, which locates the companion in the so-called “brown dwarf” desert (Marcy & Butler 2000) around a low-mass star. GJ1046 b was discovered with only 14 high precision Doppler measurements taken with UVES (VLT-UT2; Dekker et al. 2000), which, given the large RV semi-amplitude of ~1830 ms⁻¹, were sufficient to constrain the orbit. Yet, the somewhat sparse phase coverage of the orbit may lead to model ambiguity, such as two near resonant companions masking as one eccentric orbit (see Anglada-Escudé et al. 2010; Wittenmyer et al. 2013; Kürster et al. 2015), or an orbital period that could in fact be approximately twice the reported one (see Fig.1 in Kürster et al. 2008). Therefore, we have continued observing GJ1046 over the years in an attempt to constrain the orbit better.

In this paper we present new precise Doppler data of GJ1046 taken between November 2005 and July 2018 with the HARPS (Mayor et al. 2003) and FEROS (Kaufer et al. 1999) high-resolution spectographs. In addition, we provide a new stellar mass estimate of GJ1046 and we update the orbital parameters of the GJ1046 system. These new data and analysis could be used together with the GAIA epoch astrometry, when available, for breaking the sin i degeneracy and revealing the true mass of the GJ1046 system.

HARPS AND FEROS OBSERVATIONS AND DATA REDUCTION

GJ1046 is part of our HARPS and FEROS RV monitoring program of a sample of 36 southern stars, which are known to host a single moderately eccentric sub-stellar companion (Trifonov et al. 2017). Given the published UVES data of GJ1046 we were unable to completely refute the existence of a second companion, and thus we decided to obtain more Doppler measurements for this target. We did not find a second companion for GJ1046, but our RV data are valuable to determine accurately the spectroscopic orbital properties of the system.

We process the FEROS spectra using the CERES pipeline (Brahm et al. 2017), whereas the HARPS spectra were re-processed using SERVAL (Zechmeister et al. 2018), which is shown to provide a better precision than the ESO-DRS
Figure 1. Archival and new precise Doppler measurements of GJ1046. The left panel shows time series data from UVES, FEROS, HARPS and HARPS+ fitted with a Keplerian model. The right panel shows the phase-folded model and RVs at the best fit period. FEROS RVs have larger scatter when compared with UVES and HARPS, but are adequate for the determination of the orbit.

pipeline for M dwarfs (e.g. see Trifonov et al. 2018; Kaminski et al. 2018). We reduced a total of 34 FEROS and 27 HARPS spectra, achieving a mean RV precision of 14.5 ms$^{-1}$ and 1.8 ms$^{-1}$, respectively. However, we split the HARPS data into two separate temporal subsets, HARPS and HARPS+, pertinent to before and after the HARPS fibre upgrade in June 2015, respectively, which introduced an RV offset (Lo Curto et al. 2015).

NEW ORBITAL AND STELLAR MASS ESTIMATES

We model the available Doppler data of GJ1046 using a downhill Simplex algorithm (Nelder & Mead 1965; Press et al. 1992), which optimizes simultaneously the parameters of a Keplerian model, the RV data offsets, and the RV data jitter noise (Baluc and 2009). We estimate the orbital parameter uncertainties of the best fit by adopting the 1σ confidence levels of the parameter posterior distribution sampled with the emcee MCMC sampler (Foreman-Mackey et al. 2013). Our best fit yields the following values: Semi-amplitude $K_b = 1827.0^{\pm2.4}_{-1.2}$ ms$^{-1}$, period $P_b = 168.844^{+0.001}_{-0.005}$ days, eccentricity $e_b = 0.2788^{+0.001}_{-0.001}$, argument of periastron $\omega_b = 92.24^{+0.39}_{-0.14}$ deg, and time of periastron passage $t_{\omega_b} = 2453225.516^{+0.119}_{-0.120}$ BJD. These estimates are consistent with those in Kürster et al. (2008), but the uncertainties are considerably smaller.

To estimate the stellar mass of GJ1046 we constructed a new mass-luminosity relation by combining the data originally used by Benedict et al. (2016) and Delfosse et al. (2000) for their K-band mass-luminosity relations. We also included the Sun and TRAPPIST-1 (Gillon et al. 2016) K-band-masses in order to constrain the high and the low ends of the relation. The best-fit polynomial of the type $M = a_0 + a_1 K + a_4 K^4$ has the following coefficients; $a_0 = 1.735^{+0.005}_{-0.005}$, $a_1 = -0.2262^{+0.0016}_{-0.0016}$, $a_4 = 0.000062^{+0.000016}_{-0.000016}$. With an estimated distance from the Gaia DR2 parallax of $d = 15.19^{+0.03}_{-0.03}$ pc (Bailer-Jones et al. 2018) and an absolute K-magnitude of $K_{abs} = 6.12^{+0.02}_{-0.02}$ mag, the resulting mass of GJ1046 is $M = 0.437^{+0.012}_{-0.012} M_\odot$, yielding an orbital semi-major axis of $a_b = 0.463^{+0.004}_{-0.004}$ au and a minimum companion mass $m \sin i_b = 28.6^{+0.51}_{-0.51} M_{\text{Jup}}$.

CONCLUSIONS

GJ1046 b has a minimum mass consistent with a brown dwarf companion and a very small orbital separation of 0.463 au. Only a small number of similar objects are known around M dwarfs. However, the possibility that the substellar companion could be of a stellar nature still remains. As in Kürster et al. (2008) we tried to fit the astrometric orbit to the Hipparcos data taking the more accurate parallax and proper motions from TGAS, but could not significantly improve on the known range of possible inclinations. With the release of the GAIA epoch astrometry and the Doppler data presented here this degeneracy should be resolved.

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REFERENCES

Anglada-Escudé, G., López-Morales, M., & Chambers, J. E. 2010, ApJ, 709, 168, doi: 10.1088/0004-637X/709/1/168

Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Mantelet, G., & Andrae, R. 2018, ArXiv e-prints. https://arxiv.org/abs/1804.10121

Baluev, R. V. 2009, MNRAS, 393, 969, doi: 10.1111/j.1365-2966.2008.14217.x

Benedict, G. F., Henry, T. J., Franz, O. G., et al. 2016, AJ, 152, 141, doi: 10.3847/0004-6256/152/5/141

Brahm, R., Jordán, A., & Espinoza, N. 2017, PASP, 129, 034002, doi: 10.1088/1538-3873/aa5455

Dekker, H., D’Odorico, S., Kaufer, A., Delabre, B., & Kotzlowski, H. 2000, in Proc. SPIE, Vol. 4008, Optical and IR Telescope Instrumentation and Detectors, ed. M. Iye & A. F. Moorwood, 534–545

Delfosse, X., Forveille, T., Ségransan, D., et al. 2000, A&A, 364, 217

Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306, doi: 10.1086/670067

Gillon, M., Jehin, E., Lederer, S. M., et al. 2016, Nature, 533, 221, doi: 10.1038/nature17448

Kaminski, A., Trifonov, T., Caballero, J. A., et al. 2018, ArXiv e-prints. https://arxiv.org/abs/1808.01183

Kaufer, A., Stahl, O., Tubbesing, S., et al. 1999, The Messenger, 95, 8

Kürster, M., Endl, M., & Reffert, S. 2008, A&A, 483, 869, doi: 10.1051/0004-6361:200809419

Kürster, M., Trifonov, T., Reffert, S., Kostogryz, N. M., & Rodler, F. 2015, A&A, 577, A103, doi: 10.1051/0004-6361/201525872

Lo Curto, G., Pepe, F., Avila, G., et al. 2015, The Messenger, 162, 9

Marcy, G. W., & Butler, R. P. 2000, PASP, 112, 137, doi: 10.1086/316516

Mayor, M., Pepe, F., Queloz, D., et al. 2003, The Messenger, 114, 20

Nelder, J. A., & Mead, R. 1965, Computer Journal, 7, 308

Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical recipes in FORTRAN. The art of scientific computing

Trifonov, T., Kürster, M., Zechmeister, M., et al. 2017, A&A, 602, L8, doi: 10.1051/0004-6361/201731044

—. 2018, A&A, 609, A117, doi: 10.1051/0004-6361/201731442

Wittenmyer, R. A., Wang, S., Horner, J., et al. 2013, ApJS, 208, 2, doi: 10.1088/0067-0049/208/1/2

Zechmeister, M., Reiners, A., Amado, P. J., et al. 2018, A&A, 609, A12, doi: 10.1051/0004-6361/201731483
Table 1. Doppler measurements of GJ 1046

| Epoch [JD] | RV [m s\(^{-1}\)] | \(\sigma_{RV}\) | instrument |
|------------|-----------------|---------------|-------------|
| 2453690.718 | 1561.42         | 13.00         | FEROS       |
| 2454396.742 | 1108.61         | 1.59          | HARPS       |
| 2454397.609 | 1031.69         | 1.87          | HARPS       |
| 2454397.870 | 1006.97         | 1.55          | HARPS       |
| 2454399.673 | 827.51          | 1.65          | HARPS       |
| 2454424.707 | -1670.90        | 1.78          | HARPS       |
| 2454448.629 | -1582.85        | 2.90          | HARPS       |
| 2454781.669 | -1726.28        | 10.70         | FEROS       |
| 2454783.659 | -1672.98        | 10.10         | FEROS       |
| 2454787.625 | -1527.48        | 11.40         | FEROS       |
| 2454840.601 | 539.12          | 13.00         | FEROS       |
| 2454844.623 | 627.52          | 11.20         | FEROS       |
| 2454986.924 | -357.58         | 20.10         | FEROS       |
| 2455005.944 | 356.32          | 13.10         | FEROS       |
| 2455053.893 | 1799.62         | 13.50         | FEROS       |
| 2455063.896 | 1662.32         | 16.80         | FEROS       |
| 2455075.724 | 781.42          | 16.60         | FEROS       |
| 2455077.857 | 538.92          | 13.00         | FEROS       |
| 2455104.772 | -1814.68        | 12.50         | FEROS       |
| 2455116.730 | 18.92           | 11.60         | FEROS       |
| 2455201.608 | 1377.72         | 12.70         | FEROS       |
| 2455204.626 | 1495.52         | 12.80         | FEROS       |
| 2455355.908 | 818.82          | 16.50         | FEROS       |
| 2455407.855 | 1248.82         | 15.30         | FEROS       |
| 2455443.630 | -1862.18        | 18.30         | FEROS       |
| 2455926.585 | -40.96          | 1.73          | HARPS       |
| 2457561.879 | 1236.85         | 1.77          | HARPS+      |
| 2457561.900 | 1235.40         | 1.36          | HARPS+      |
| 2457561.920 | 1235.66         | 1.28          | HARPS+      |
| 2457609.839 | 592.35          | 1.10          | HARPS+      |
| 2457609.860 | 590.40          | 1.07          | HARPS+      |
| 2457609.881 | 590.89          | 1.16          | HARPS+      |
| 2457611.850 | 351.43          | 1.15          | HARPS+      |
| 2457611.872 | 352.78          | 1.13          | HARPS+      |
Table 2. Doppler measurements of GJ 1046 (continue)

| Epoch [JD] | RV [m s$^{-1}$] | $\sigma_{RV}$ | instrument |
|------------|-----------------|---------------|------------|
| 2457611.892 | 351.20          | 1.03          | HARPS+     |
| 2457611.933 | 344.97          | 1.20          | HARPS+     |
| 2457611.957 | 329.34          | 11.68         | HARPS+     |
| 2457956.924 | -592.08         | 13.80         | FEROS      |
| 2457964.933 | -1350.88        | 13.30         | FEROS      |
| 2457979.823 | -1856.78        | 14.10         | FEROS      |
| 2457980.911 | -1834.98        | 14.70         | FEROS      |
| 2457982.852 | -1832.58        | 12.40         | FEROS      |
| 2457984.809 | -1859.88        | 22.70         | FEROS      |
| 2458002.826 | -1325.88        | 15.60         | FEROS      |
| 2458029.742 | -276.68         | 16.30         | FEROS      |
| 2458036.696 | 59.02           | 13.40         | FEROS      |
| 2458054.743 | 731.52          | 18.90         | FEROS      |
| 2458061.627 | 998.92          | 13.60         | FEROS      |
| 2458084.626 | 1697.03         | 1.38          | HARPS+     |
| 2458084.648 | 1699.84         | 1.34          | HARPS+     |
| 2458084.669 | 1694.68         | 1.56          | HARPS+     |
| 2458085.648 | 1713.41         | 1.58          | HARPS+     |
| 2458085.670 | 1714.37         | 1.27          | HARPS+     |
| 2458085.691 | 1716.77         | 1.27          | HARPS+     |
| 2458093.601 | 1792.52         | 15.10         | FEROS      |
| 2458100.607 | 1696.22         | 16.90         | FEROS      |
| 2458134.585 | -1392.78        | 16.90         | FEROS      |
| 2458153.546 | -1826.28        | 14.60         | FEROS      |
| 2458324.896 | -1763.12        | 2.30          | HARPS+     |
| 2458324.917 | -1766.98        | 1.55          | HARPS+     |
| 2458324.938 | -1769.52        | 2.09          | HARPS+     |

Note—The UVES RVs can be found in Kürster et al. (2008). In the RV analysis we used nightly averaged values of these measurements. RVs presented in the table are with best fit RV offsets subtracted. For the four data sets these RV offsets are:

$\gamma_{\text{UVES}} = -69.29^{+1.98}_{-1.44} \text{ m s}^{-1}$, $\gamma_{\text{FEROS}} = 63159.42^{+4.79}_{-4.15} \text{ m s}^{-1}$, $\gamma_{\text{HARPS}} = -394.29^{+2.69}_{-2.05} \text{ m s}^{-1}$, $\gamma_{\text{HARPS+}} = -348.18^{+4.11}_{-3.21} \text{ m s}^{-1}$. 