

# The HARPS search for southern extra-solar planets<sup>★,★★</sup>

## XXVI. Two giant planets around M0 dwarfs

T. Forveille<sup>1</sup>, X. Bonfils<sup>1,2</sup>, G. Lo Curto<sup>3</sup>, X. Delfosse<sup>1</sup>, S. Udry<sup>2</sup>, F. Bouchy<sup>4,5</sup>, C. Lovis<sup>2</sup>, M. Mayor<sup>2</sup>, C. Moutou<sup>6</sup>,  
D. Naef<sup>2,3</sup>, F. Pepe<sup>2</sup>, C. Perrier<sup>1</sup>, D. Queloz<sup>2</sup>, and N. Santos<sup>7,8</sup>

<sup>1</sup> Laboratoire d'Astrophysique de Grenoble, Observatoire de Grenoble, Université Joseph Fourier, CNRS, UMR 5571, BP 53, 38041 Grenoble Cedex 9, France

e-mail: [Thierry.Forveille@obs.ujf-grenoble.fr](mailto:Thierry.Forveille@obs.ujf-grenoble.fr)

<sup>2</sup> Observatoire de Genève, Université de Genève, 51 ch. des Maillettes, 1290 Sauverny, Switzerland

<sup>3</sup> European Southern Observatory, Alonso de Cordova 3107, Vitacura, Santiago, Chile

<sup>4</sup> Institut d'Astrophysique de Paris, CNRS, Université Pierre et Marie Curie, 98bis Bd Arago, 75014 Paris, France

<sup>5</sup> Observatoire de Haute-Provence, CNRS/OAMP, 04870 St Michel l'Observatoire, France

<sup>6</sup> Laboratoire d'Astrophysique de Marseille, 38 rue Frédéric Joliot-Curie, 13388 Marseille Cedex 13, France

<sup>7</sup> Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal

<sup>8</sup> Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal

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### ABSTRACT

Fewer giant planets are found around M dwarfs than around more massive stars, and this dependence of planetary characteristics on the mass of the central star is an important observational diagnostic of planetary formation theories. In part to improve on those statistics, we are monitoring the radial velocities of nearby M dwarfs with the *HARPS* spectrograph on the ESO 3.6 m telescope. We present here the detection of giant planets around two nearby M0 dwarfs: planets, with minimum masses of respectively 5 Jupiter masses and 1 Saturn mass, orbit around Gl 676A and HIP 12961. The latter is, by over a factor of two, the most massive planet found by radial velocity monitoring of an M dwarf, but its being found around an early M-dwarf is in approximate line with the upper envelope of the planetary vs stellar mass diagram. HIP 12961 ([Fe/H] = -0.07) is slightly more metal-rich than the average solar neighborhood ([Fe/H] = -0.17), and Gl 676A ([Fe/H] = 0.18) significantly so. The two stars together therefore reinforce the growing trend for giant planets being more frequent around more metal-rich M dwarfs, and the 5 Jupiter mass Gl 676Ab being found around a metal-rich star is consistent with the expectation that the most massive planets preferentially form in disks with large condensate masses.

**Key words.** stars: individual: Gl 676A – stars: individual: HIP 12961 – planetary systems – stars: late-type – techniques: radial velocities – stars: low-mass

## 1. Introduction

Much recent theoretical work has gone into examining how planet formation depends on stellar mass, because stellar mass significantly changes the physical conditions which control the formation of planets. A comparison, for instance, of the planet populations around Sun-like stars on one hand, and around M dwarfs on the other hand, probes the sensitivity of the planetary formation process to several physical parameters: around lower mass stars gravity (hence disk rotation speed), temperature (which regulates the position of the ice line) are both lower, and, perhaps most importantly, disk mass scales approximately linearly with stellar mass (e.g. [Scholz et al. 2006](#)).

Within the “core accretion” paradigm, [Laughlin et al. \(2004\)](#), [Ida & Lin \(2005\)](#), and [Kennedy & Kenyon \(2008\)](#) all predict that giant planet formation is inhibited around very-low-mass

stars, while Neptune-mass planets should inversely be common. Within the same paradigm, but assuming that the properties of protoplanetary disks, contrary to observations, do not change with stellar mass, [Kornet et al. \(2006\)](#) predict instead that Jupiter-mass planets become more frequent in inverse proportion to the stellar mass. Finally, [Boss \(2006\)](#) examines how planet formation depends on stellar mass for planets formed by disk instability, and concludes that the frequency of Jupiter-mass planet is largely independent of stellar mass, as long as disks are massive enough to become unstable. One needs to note, though, that proto-planetary disks of a realistic mass are likely to be gravitationally stable out to at least 10 AU. Planets can thus form through gravitational instability only beyond that distance, in a separation range only skimmed by radial velocity monitoring and probed mostly by microlensing searches and direct imaging. Massive planets formed by gravitational instability and found well within 5 AU must thus then have migrated inward. How giant planets migrating in the massive disks needed for gravitational instability can escape accreting enough mass to become a brown dwarf ( $>13 M_{\text{Jup}}$ ) is unclear (e.g. [Stamatellos & Whitworth 2009](#); [Kratter et al. 2010](#)).

\* Based on observations made with the HARPS instrument on the ESO 3.6-m telescope at La Silla Observatory under program ID 072.C-0488

\*\* Tables 3 and 4 are also available in electronic form at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](ftp://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/cgi-bin/qcat?J/A+A/526/A141>

Observationally, just a dozen of the close to 400 planetary systems currently known from radial velocity monitoring, are centered around M dwarfs ( $M < 0.6 M_{\odot}$ )<sup>1</sup>. This no doubt reflects in part a selection bias, since many more of the intrinsically brighter solar-type stars than of the fainter M dwarfs have been searched for planets, but there is increasing statistical evidence (e.g. Bonfils et al. 2006; Endl et al. 2006; Johnson et al. 2007, 2010) that M dwarfs also genuinely have fewer massive planets ( $\sim M_{\text{Jup}}$ ) than the more massive solar-type stars. They may, on the other hand, and though no rigorous statistical analysis has yet been performed for that planet population, have a larger prevalence of the harder to detect Neptune-mass and super-Earth planets: a quarter of the  $\sim 30$  planets with  $M \sin(i) < 0.1 M_{\text{Jup}}$  known to date orbit an M dwarf, when solar-type stars outnumber M dwarfs by an order of magnitude in planet-search samples. Conversely, the highest mass planets known around M dwarfs are the  $M \sin(i) = 2 M_{\text{Jup}}$  Gl 876b (Delfosse et al. 1998; Marcy et al. 1998) and HIP79431b (Apps et al. 2010), and at a larger orbital separation of  $\sim 3$  AUs the  $M \approx 3.5 M_{\text{Jup}}$  OGLE-2005-BLG-071Lb microlensing planet (Dong et al. 2009), when over two dozen planets with masses over  $10 M_{\text{Jup}}$  are known around solar type stars. The statistical significance of that difference however remains modest, since the M dwarfs searched for planets only number in the few hundreds, when the apparent fraction of these very massive planets is under 1% around solar type stars.

We present here the detection of two giant planets around M0 dwarfs, a  $M \sin(i) = 0.354 M_{\text{Jup}}$  planet around HIP 12961, and a  $M \sin(i) = 4.87 M_{\text{Jup}}$  planet around Gl 676A.

## 2. Stellar characteristics

Table 1 summarizes the properties of the two host stars, which we briefly discuss below.

### 2.1. HIP 12961

HIP 12961 (also CD-23deg1056, LTT 1349, NLTT 8966, SAO 168043) was not identified as a member of the 25 pc volume until the publication of the Perryman & ESA (1997) catalog, and has attracted very little attention: it is mentioned in just 4 literature references, and always as part of a large catalog. Because HIP 1291 does not figure in the Gliese & Jahreiß (1991) catalog, it was omitted from the Hawley et al. (1996) spectral atlas of the late-type nearby stars. SIMBAD shows an M0 spectral type, which seems to trace back to a classification of untraceable pedigree listed in the NLTT catalog (Luyten 1980), while Stephenson (1986) estimated a K5 type from low-dispersion objective prism photographic plates. The absolute magnitude and color of HIP 12961,  $M_V = 8.50$  and  $V - K = 3.57$ , suggest that its older NLTT spectral type is closer to truth (e.g. Leggett 1992). We adopt this spectral type for the remainder of the paper, but note that a modern classification from a digital low resolution spectrum is desirable. HIP 12961 has fairly strong chromospheric activity, with 90% of stars with spectral types K7 to M1 in the HARPS radial velocity sample (which however reject the most active stars) having weaker CaII H and K lines, and just 10% stronger lines. The 2MASS photometry (Table 1) and the Leggett et al. (2001)  $J - K$  colour vs bolometric relation result in a K-band bolometric correction of  $BC_K = 2.61$ , and together with the parallax in a  $0.076 L_{\odot}$  luminosity.

<sup>1</sup> <http://exoplanet.eu/catalog-RV.php>

**Table 1.** Observed and inferred stellar parameters for Gl 676A and HIP 12961.

Parameter	Gl 676A	HIP 12961	Notes
Spectral Type	M0V	M0V	<sup>a</sup>
$V$	$9.585 \pm 0.006$	$10.31 \pm 0.04$	<sup>b</sup>
$J$	$6.711 \pm 0.020$	$7.558 \pm 0.021$	<sup>c</sup>
$K_s$	$5.825 \pm 0.029$	$6.736 \pm 0.018$	<sup>c</sup>
$BC_{K_s}$	2.73	2.61	<sup>d</sup>
$\pi$ [mas]	$60.79 \pm 1.62$	$43.45 \pm 1.72$	<sup>e</sup>
Distance [pc]	$16.45 \pm 0.44$	$23.01 \pm 0.91$	
$M_V$	$8.50 \pm 0.06$	$8.50 \pm 0.09$	
$M_{K_s}$	$4.74 \pm 0.06$	$4.93 \pm 0.09$	
$M_{\text{bol}}$	7.47	7.54	
$L_{\star}$ [ $L_{\odot}$ ]	0.082	0.076	
$v \sin i$ [ $\text{km s}^{-1}$ ]	$1.6 \pm 1.0$	$1.5 \pm 1.0$	
[Fe/H]	0.18	-0.07	<sup>f</sup>
$M_{\star}$ [ $M_{\odot}$ ]	0.71	0.67	<sup>g</sup>

**Notes.** (<sup>a</sup>) Hawley et al. (1996) for Gl 676A, and Luyten (1980) for HIP 12961; (<sup>b</sup>) Koen et al. (2002) for Gl 676A, and computed from the TYCHO ( $B_T, V_T$ ) photometry for HIP 12961; (<sup>c</sup>) Skrutskie et al. (2006); (<sup>d</sup>) computed from  $J - K_s$  with the Leggett et al. (2001)  $BC_{K_s}$  vs.  $J - K_s$  relation; (<sup>e</sup>) van Leeuwen (2007); (<sup>f</sup>) computed from  $M_{K_s}$  and  $V - K_s$  using the Schlafman & Laughlin (2010) calibration; (<sup>g</sup>) computed from  $M_{K_s}$  using the Delfosse et al. (2000) calibration; both masses are at the upper edge of the validity range of that calibration, and they might therefore have somewhat larger errors than its 10% dispersion.

### 2.2. Gl 676A

The Gl 676 system (also CCDM J17302-5138) has been recognized as a member of the immediate solar neighborhood for much longer, figuring in the original Gliese (1969) catalog of the 20 pc volume. It consequently has 15 references listed in SIMBAD, though none of those dedicates more than a few sentences to Gl 676. The system comprises Gl 676A (also CD -51 10924, HIP 85647, CPD-51 10396) and Gl 676B, with respective spectral types of M0V and M3V (Hawley et al. 1996) and separated by  $\sim 50''$  on the sky. At the distance of the system this angular distance translates into an  $\sim 800$  AU projected separation, which is probably far enough that Gl 676B didn't strongly influence the formation of the planetary system of Gl 676A. Gl 676A is a moderately active star, with a CaII H and K emission strength at the third quartile of the cumulative distribution for stars with spectral types between K7 and M1 in the HARPS radial velocity sample. The 2MASS photometry (Table 1) and the Leggett et al. (2001)  $J - K$  colour-bolometric relation result in a K-band bolometric correction of  $BC_K = 2.73$ , and together with the parallax in a  $0.082 L_{\odot}$  luminosity. The Delfosse et al. (2000) K-band Mass-Luminosity relation results in masses of respectively 0.71 and  $0.29 M_{\odot}$  for Gl 676A and Gl 676B. The former is at the edge of the validity range of the Delfosse et al. (2000) calibration, and might therefore have somewhat larger uncertainties than the  $\sim 10\%$  dispersion in that calibration.

## 3. HARPS Doppler measurements and orbital analysis

We obtained measurements of Gl 676A and HIP 12961 with HARPS (High Accuracy Radial velocity Planet Searcher, Mayor et al. 2003), as part of the guaranteed-time program of the instrument consortium. HARPS is a high-resolution ( $R = 115\,000$ ) fiber-fed echelle spectrograph, optimized for planet search programs and asteroseismology. It is the most precise

spectro-velocimeter to date, with a long-term instrumental RV accuracy well under  $1 \text{ m s}^{-1}$  (e.g. Lovis et al. 2006; Mayor et al. 2009). When it aims for ultimate radial velocity precision, HARPS uses simultaneous exposures of a thorium lamp through a calibration fiber. For the present observations however, we relied instead on its excellent instrumental stability (nightly instrumental drifts  $<1 \text{ m s}^{-1}$ ). Both targets are too faint for us to reach the stability limit of HARPS within realistic integration times, and dispensing with the simultaneous thorium light produces cleaner stellar spectra, more easily amenable to quantitative spectroscopic analysis. The two stars were observed as part of the volume-limited HARPS search for planets (e.g. Moutou et al. 2009; Lo Curto et al. 2010). While generally referred to as F-G-K stars, for the sake of concision, the targets of that program actually include M0 dwarfs (Lo Curto et al. 2010).

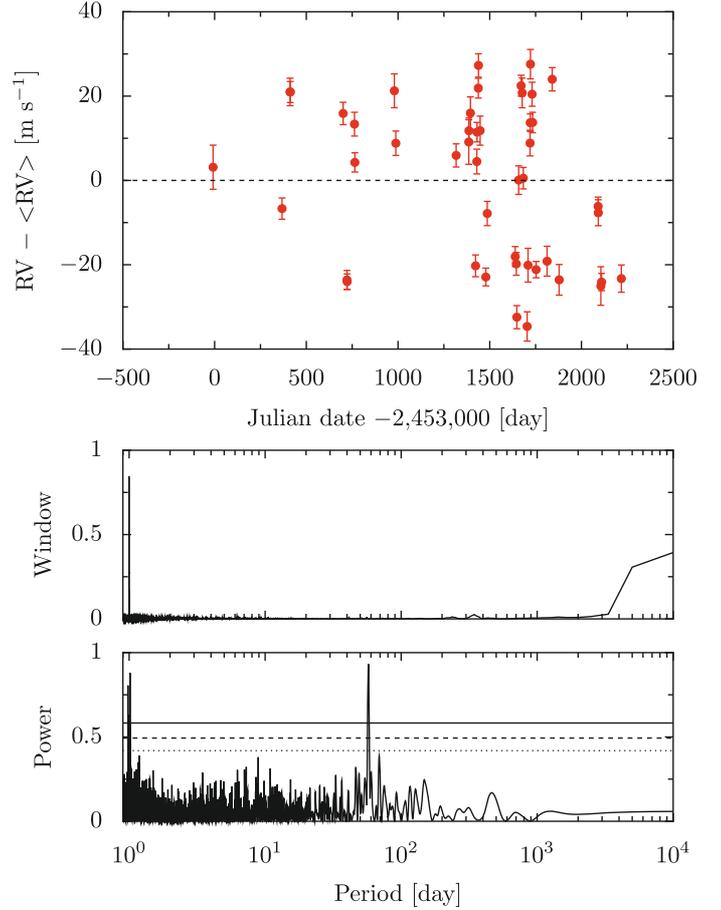
We used 15 mn exposures for both stars, obtaining median S/N ratios (per pixel at 550 nm) of 53 for the  $V = 9.58$  Gl 676A, and 49 for the  $V = 10.31$  HIP 12961. The 69 and 46 radial velocities of Gl 676A and HIP 12961 (Tables 3 and 4, also available at CDS) were obtained with the standard HARPS reduction pipeline, based on cross-correlation with a stellar mask and on a precise nightly wavelength calibration from ThAr spectra (Lovis & Pepe 2007). The median internal errors of these velocities are respectively  $1.9$  and  $2.8 \text{ m s}^{-1}$ , and include a  $\sim 0.2 \text{ m s}^{-1}$  noise on the nightly zero-point measurement, a  $\sim 0.3 \text{ m s}^{-1}$  uncertainty on the instrumental drift, and the photon noise computed from the full Doppler information content of the spectra (Bouchy et al. 2001). The photon noise contribution completely dominates the error budget for these moderately faint sources.

### 3.1. A Saturn-mass planet around HIP 12961

The computed radial velocities of HIP 12961 vary with a  $\sim 60 \text{ m s}^{-1}$  peak to peak amplitude (Fig. 1, top panel), an order of magnitude above their  $2.6 \text{ m s}^{-1}$  average photon noise, and well above the  $\lesssim 1 \text{ m s}^{-1}$  maximum jitter expected from the chromospheric activity. The variations show no correlation with the bisector span (rms  $6 \text{ m s}^{-1}$ ), the depth (10.65%, with 0.07% rms) or width ( $3.566 \text{ km s}^{-1}$ , with  $14 \text{ m s}^{-1}$  rms) of the correlation profile, or any of the standard stellar activity diagnostic, making orbital motion by far their most likely cause. The Lomb-Scargle periodogram of the velocities shows one highly significant peak at 57.45 days (Fig. 1, middle and bottom panel), as well as its 4 aliases at  $\pm 1$  sidereal and civil days. Phasing of the velocities on that period shows well sampled smooth variations (Fig. 2 top panel). A Keplerian fit (Table 2) yields a moderately eccentric orbit ( $e = 0.2$ ) with a  $25 \text{ m s}^{-1}$  semi-amplitude.

The rms amplitude of the residuals from that orbit is  $3.8 \text{ m s}^{-1}$  (Fig. 2, middle panel), significantly above the  $2.6 \text{ m s}^{-1}$  average photon noise. The square root of the reduced  $\chi^2$  of the fit is consequently 1.5. The radial velocities may therefore contain information beyond the detected planet, but the highest peak in the periodogram of the radial velocity residuals (16.6 days) only has  $2\sigma$  significance. It also coincides with a signal in the periodogram of the correlation profile's depth, and it is broadly consistent with the stellar rotation period expected from the significant chromospheric activity. This peak, if not just noise, is therefore much more likely to reflect rotational modulation of stellar spots than a planet. There is no current evidence for additional planets in the system.

Together with the  $0.67 M_{\odot}$  (Table 1) stellar mass, the orbital parameters translate into a minimum companion mass of  $0.35 M_{\text{Jup}}$ , or 1.2 Saturn-mass, with a 0.25 AU semi-major axis. For an Earth-like albedo of 0.35 the equilibrium temperature at



**Fig. 1.** HARPS radial velocities of HIP 12961 as a function of barycentric Julian day (*top panel*), spectral power window (*middle panel*) and Lomb-Scargle periodogram of these velocities (*bottom panel*). The horizontal lines mark false alarm probabilities equivalent to 1, 2 and 3 sigmas significance levels for Gaussian noise.

**Table 2.** Orbital elements for the Keplerian orbital models of HIP 12961 and Gl 676A.

Element	HIP 12961	Gl 676A
$\gamma$ [ $\text{km s}^{-1}$ ]	$33.0463 \pm 0.0014$	$-39.108 \pm 0.091$
$dy/dr$ [ $\text{m s}^{-1} \text{ yr}^{-1}$ ]	–	$10.66 \pm 0.61$
Epoch [BJD]	–	2450000
$P$ [days]	$57.435 \pm 0.042$	$1056.8 \pm 2.8$
$e$	$0.166 \pm 0.034$	$0.326 \pm 0.009$
$\omega$ [deg.]	$272 \pm 13$	$85.7 \pm 1.4$
$T_0$ [BJD]	$2454428.4 \pm 2.0$	$2455411.9 \pm 3.0$
$K_1$ [ $\text{m s}^{-1}$ ]	$24.71 \pm 0.86$	$129.3 \pm 1.2$
$a$ [AU]	0.25	1.82
$M \sin(i)$ [ $M_{\text{Jup}}$ ]	0.35	4.9
$\sigma(\text{O-C})$ [ $\text{m s}^{-1}$ ]	3.9	3.4
$N_{\text{mes}}$	46	69
$N_{\text{par}}$	6	7
$\chi_r^2$	2.3	3.9

that distance from a  $0.076 L_{\odot}$  (Table 1) luminosity star is 263 K, slightly higher than the terrestrial 255 K but below the  $\sim 270 \text{ K}$  threshold for triggering a runaway greenhouse effect (Selsis et al. 2007). A putative massive moon of HIP 12961b could therefore be potentially hospitable to life.

The a priori geometric probability that HIP 12961b transits across HIP 12961 is approximately 1%. As usual for planets of

**Table 3.** Radial-velocity measurements and error bars for Gl 676A.

JD-2400000	RV [km s <sup>-1</sup> ]	Uncertainty [km s <sup>-1</sup> ]
53917.747997	-39.097817	0.002411
53919.735174	-39.094780	0.003022
54167.897856	-39.001569	0.001963
54169.895854	-39.004708	0.001784
54171.904445	-39.002836	0.001928
54232.818013	-39.002344	0.001722
54391.491808	-39.165064	0.001699
54393.489934	-39.170823	0.001861
54529.900847	-39.245590	0.002076
54547.915016	-39.242932	0.001751
54559.815698	-39.232718	0.002002
54569.903637	-39.241409	0.002270
54571.889460	-39.245083	0.001360
54582.820292	-39.232950	0.001791
54618.755585	-39.226941	0.002436
54660.661636	-39.203487	0.001727
54661.772229	-39.205488	0.001626
54662.675237	-39.212174	0.002052
54663.811590	-39.204402	0.001537
54664.790043	-39.203176	0.002240
54665.786377	-39.207272	0.001557
54666.696058	-39.208065	0.001421
54670.672602	-39.205235	0.002207
54671.603329	-39.204414	0.001945
54687.561959	-39.202682	0.001968
54721.554874	-39.187358	0.002167
54751.490690	-39.178373	0.004248
54916.819805	-39.100792	0.001226
54921.892971	-39.105131	0.002259
54930.906849	-39.097319	0.001873
54931.795103	-39.092830	0.001922
54935.817789	-39.092687	0.001131
55013.686615	-39.048271	0.001909
55013.743720	-39.054037	0.002253
55074.520060	-39.027729	0.001871
55090.507026	-39.021867	0.001839
55091.528800	-39.023418	0.004842
55098.494144	-39.025046	0.001144
55100.540947	-39.015400	0.001408
55101.490472	-39.019816	0.002182
55102.502862	-39.021444	0.003021
55104.540258	-39.020592	0.002090
55105.523635	-39.016518	0.003934
55106.519974	-39.014727	0.001956
55111.509339	-39.015782	0.001428
55113.497880	-39.013708	0.001459
55115.514997	-39.008140	0.003762
55116.487535	-39.013302	0.001343
55117.493046	-39.007306	0.002138
55121.526645	-39.006189	0.002180
55122.505321	-39.008620	0.001979
55124.497834	-39.008016	0.001203
55127.516794	-39.005698	0.001163
55128.513957	-39.002138	0.001187
55129.495404	-39.002679	0.001308
55132.495755	-39.003770	0.001430
55133.493189	-39.001253	0.001564
55259.907275	-38.961036	0.002051
55260.864406	-38.961729	0.001725
55284.893135	-38.966427	0.002793
55340.708504	-38.986337	0.002081
55355.795443	-39.004416	0.001919

**Notes.** All values are relative to the solar system barycenter, and corrected from the small perspective acceleration using the Hipparcos parallax and proper motion.

**Table 3.** continued.

JD-2400000	RV [km s <sup>-1</sup> ]	Uncertainty [km s <sup>-1</sup> ]
55375.610729	-39.030286	0.002274
55387.656686	-39.049946	0.002556
55396.537980	-39.056201	0.002343
55400.642866	-39.067768	0.001486
55401.594785	-39.063691	0.001907
55402.590925	-39.066073	0.005969
55402.702771	-39.063337	0.003840

M dwarfs, the transit would be deep ( $\sim 2.5\%$ ) and therefore well suited to high quality transmission spectroscopy of the planetary atmosphere, as well as to searches for transits by planetary moons. This high potential return offsets the long odds to some extent, and the deep transits would be within easy reach of amateur-grade equipment. The star will thus be well worth searching for transits, once additional radial velocity measurements will have narrowed down the time windows for potential planetary transits.

### 3.2. A massive long period planet around Gl 676A

The computed velocities of Gl 676A (Table 3) exhibit unambiguous variations of several hundred  $\text{m s}^{-1}$  with a period slightly over our current observing span, superimposed upon a slower drift (Fig. 3, upper panel). The correlation profile depth (13.61%, with 0.12% rms), its width, the bisector span ( $5 \text{ m s}^{-1}$  rms), and the chromospheric indices show no systematic variations that would correlate with the radial velocity changes.

A fit of a Keplerian plus a constant acceleration to the radial velocities (Table 2) yields a period of  $1056.8 \pm 2.8$  days, a semi-amplitude of  $122.8 \pm 1.9 \text{ m s}^{-1}$ , and a  $10.7 \text{ m s}^{-1} \text{ yr}^{-1}$  acceleration.

Together with the  $0.71 M_{\odot}$  (Table 1) stellar mass, the orbital parameters imply a companion mass of  $4.9 M_{\text{Jup}}$  and a 1.82 AU semi-major axis. At the 16.5 pc distance of the Gl 676 system, the minimum astrometric wobble of Gl 676A, for a  $\sin(i) = 1$  edge-on orbit, is  $\pm 0.67$  mas. This is within reach of both the FGS instrument on *HST* (e.g. Martioli et al. 2010) and imagers on 8m-class telescopes (Lazorenko et al. 2009). The companion of Gl 676A therefore belongs to the small group of non-eclipsing planets for which the inclination ambiguity can potentially be lifted with existing instruments. We have started such astrometric observations using the *FORS2* imager of the ESO *VLT*.

The line of sight acceleration of Gl 676A by its  $0.3 M_{\odot}$  Gl 676B stellar companion is of order  $G M_{\text{B}}/r_{\text{AB}}^2$ , and from the 800 AU projected separation is therefore under  $0.1 \text{ m s}^{-1} \text{ yr}^{-1}$ . The two orders of magnitude discrepancy between the observed acceleration and that expected from Gl 676B demonstrates that the system contains an additional massive body. That body could be planetary if its separation is under  $\sim 15$  AU ( $0.9''$ ), stellar if that separation is above  $\sim 40$  AU ( $2.4''$ ), or a brown dwarf for intermediate separations. Adaptive optics imaging could easily narrow down these possibilities, as will the continuing radial velocity monitoring to constrain the curvature of the radial velocity trend, and the on-going astrometric effort.

The rms amplitude of the residuals around the Keplerian+acceleration orbit is  $3.4 \text{ m s}^{-1}$ , significantly above our  $1.7 \text{ m s}^{-1}$  average measurement error. The square root of the reduced  $\chi^2$  of the fit is consequently 2.0, indicating that the residuals contain structure above the photon noise. The highest peak in a Lomb-Scargle (Lomb 1976; Scargle 1982) periodogram of the

**Table 4.** Radial-velocity measurements and error bars for HIP 12961.

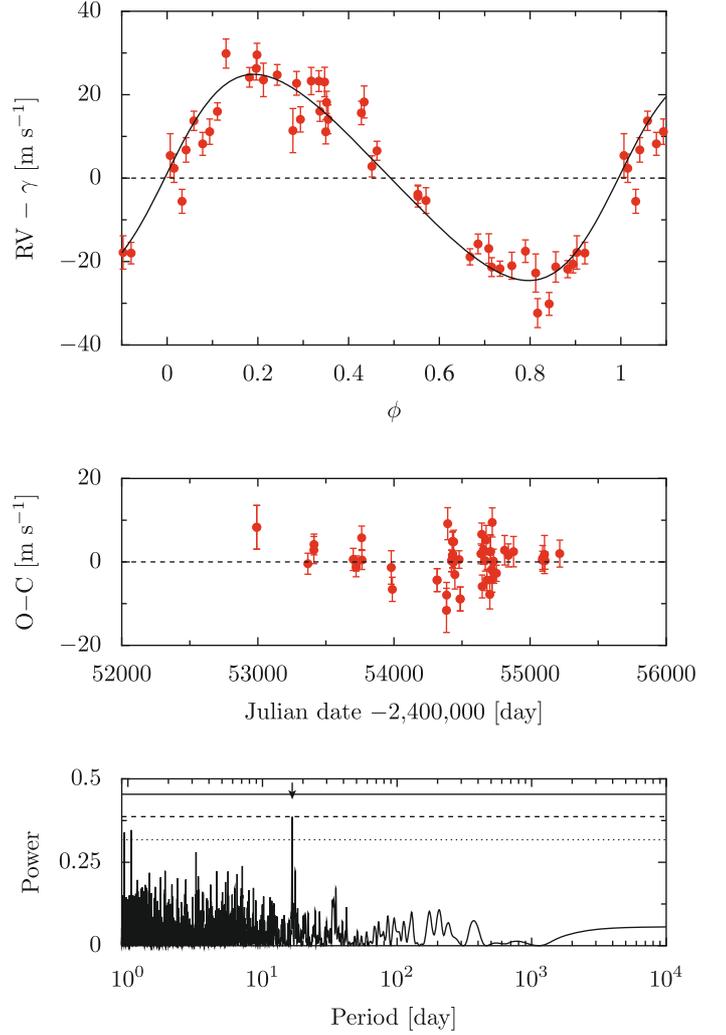
JD-2400000	RV [km s <sup>-1</sup> ]	Uncertainty [km s <sup>-1</sup> ]
52991.634308	33.05175	0.00524
53367.633702	33.04193	0.00252
53411.567881	33.06961	0.00326
53412.538676	33.06959	0.00249
53700.702601	33.06450	0.00265
53721.606360	33.02500	0.00226
53722.659901	33.02462	0.00182
53762.549717	33.06197	0.00282
53764.526469	33.05289	0.00228
53979.914378	33.06988	0.00401
53987.805086	33.05744	0.00290
54316.859111	33.05455	0.00275
54385.727404	33.05773	0.00529
54386.677499	33.06041	0.00303
54394.741029	33.06459	0.00384
54422.684669	33.02836	0.00258
54429.638114	33.05310	0.00294
54430.626508	33.06007	0.00231
54437.666007	33.07050	0.00235
54438.616998	33.07589	0.00277
54447.623874	33.06043	0.00345
54478.620266	33.02571	0.00210
54486.564941	33.04077	0.00287
54638.924339	33.03056	0.00237
54644.919198	33.02882	0.00270
54647.921380	33.01618	0.00274
54657.875027	33.04869	0.00339
54670.938132	33.07108	0.00248
54676.938113	33.06938	0.00353
54682.924974	33.04915	0.00254
54703.900626	33.01398	0.00347
54708.869197	33.02851	0.00400
54719.829342	33.05747	0.00304
54720.805422	33.06231	0.00208
54721.896983	33.07619	0.00349
54730.830908	33.06906	0.00285
54733.780908	33.06236	0.00242
54752.787477	33.02746	0.00194
54812.601219	33.02945	0.00354
54840.603108	33.07261	0.00276
54878.515553	33.02504	0.00364
55090.820449	33.04247	0.00219
55091.853089	33.04096	0.00308
55105.740055	33.02358	0.00457
55109.787500	33.02451	0.00205
55217.599913	33.02533	0.00323

**Notes.** All values are relative to the solar system barycenter, and corrected from the small perspective acceleration using the Hipparcos parallax and proper motion.

residuals however only rises to a level equivalent to a  $1 \sigma$  detection (Fig. 4). There is therefore no immediate evidence for additional planets in the system. The excess residuals may simply reflect jitter from the moderate stellar activity of Gl 676A, or alternatively they could be early signs of multiple additional planets, which additional observations would then eventually disentangle.

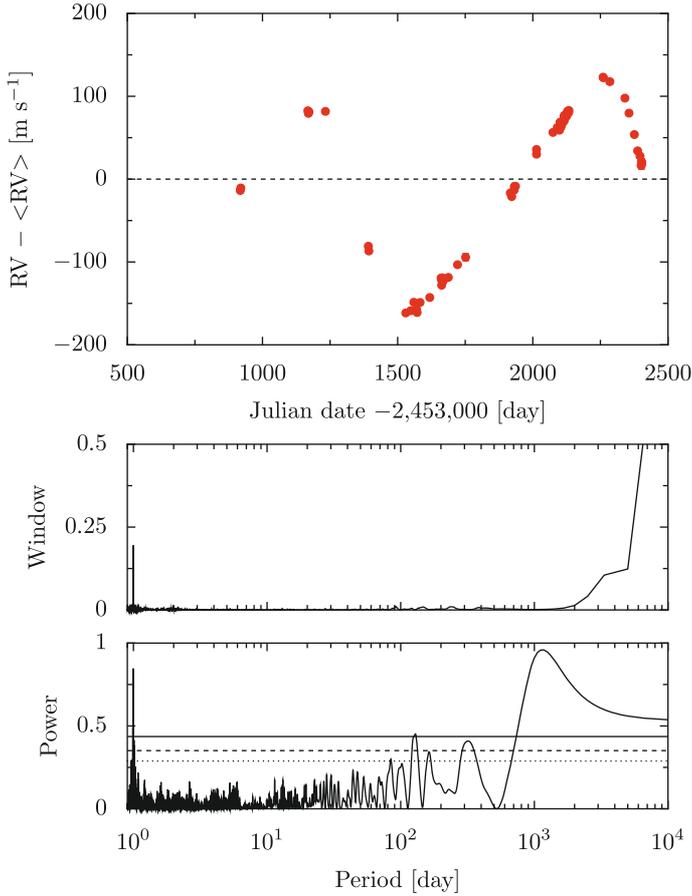
#### 4. Discussion

As discussed above, HIP 12961 and Gl 676A are orbited by giant planets with minimum masses of approximately 0.5 and 5 Jupiter masses. The latter is twice the  $M \sin(i) = 2 M_{\text{Jup}}$  of Gl 876b



**Fig. 2.** HARPS radial velocities of HIP 12961 phased to the 57.44 days period, overlaid with the adjusted Keplerian orbit (*top panel*). Residuals from the Keplerian orbit as a function of barycentric Julian day (*middle panel*), and Lomb-Scargle periodogram of these residuals (*bottom panel*). The horizontal lines mark false alarm probabilities equivalent to 1, 2 and 3 sigmas significance levels for Gaussian noise.

(Delfosse et al. 1998; Marcy et al. 1998) and HIP79431b (Apps et al. 2010), previously the highest mass planets found by radial velocity monitoring of M dwarfs, and above the 3.8 or 3.4  $M_{\text{Jup}}$  (from two degenerate solutions) of the OGLE-2005-BLG-0711b (Dong et al. 2009) microlensing planet. The M0V Gl 676A however is significantly more massive (0.71  $M_{\odot}$ , Table 1) than the M4V Gl 876 (0.33  $M_{\odot}$ , Correia et al. 2010) and the M3V HIP79431 (0.49  $M_{\odot}$ , Apps et al. 2010). The higher mass of its planet therefore remains in approximate line with the current upper envelope of the planetary versus stellar mass diagram. These most massive planets are rare at any stellar mass, with an occurrence rate under 1%, suggesting that they can form only under the most favorable conditions. They have been suggested to form through gravitational instability, with their lower mass counterparts forming by core accretion. Proto-planetary disks of any realistic mass, however, are expected to be gravitationally stable out to beyond 10 AU. If Gl 676Ab formed through gravitational instability, it would therefore have undergone much inward migration, through a very massive disk. How it could escape accreting enough mass during this migration to become a brown dwarf is unclear.

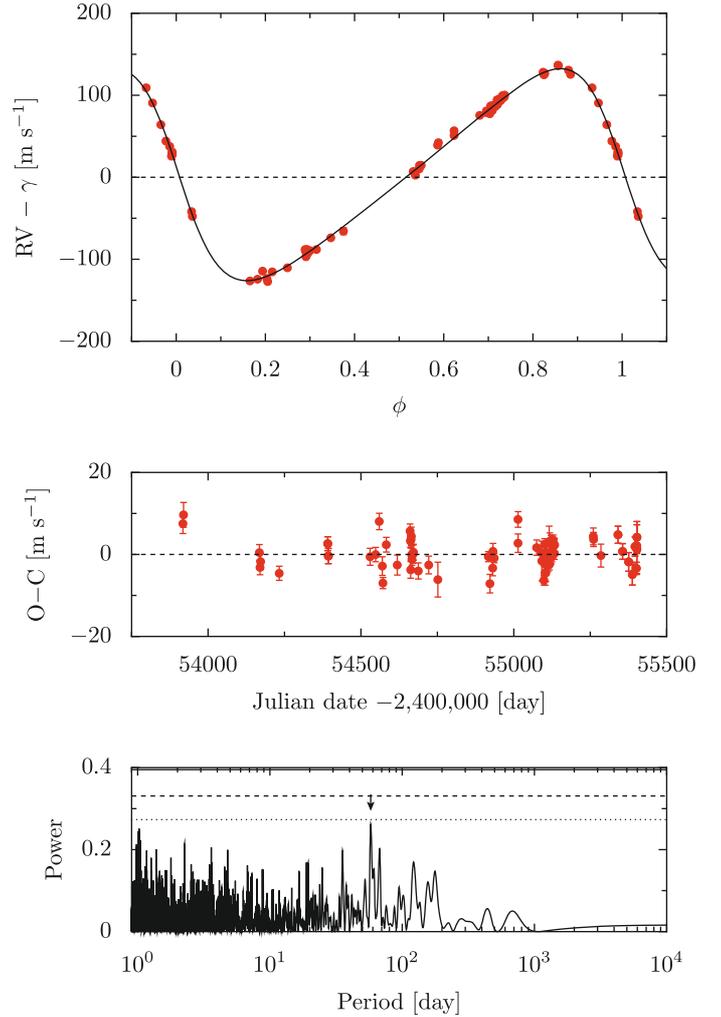


**Fig. 3.** HARPS radial velocities of Gl 676A as a function of barycentric Julian day (*top panel*), spectral power window (*middle panel*) and Lomb-Scargle periodogram of these velocities (*bottom panel*). The horizontal lines mark false alarm probabilities equivalent to 1, 2 and 3 sigma significance levels for Gaussian noise.

Gl 676A and HIP 12961 increase the sample of M dwarfs with giant planets (Saturn-mass and above) from 7 to 9, and therefore offer an opportunity to evaluate the trend (Johnson & Apps 2009; Schlaufman & Laughlin 2010) for giant planets being more common around more metal-rich M dwarfs. Adopting the very recent Schlaufman & Laughlin (2010) metallicity calibration of the  $M_{K_s}$  vs.  $V - K_s$  plane, which finds metallicities approximately half-way between those of the earlier Bonfils et al. (2005) and Johnson & Apps (2009) calibrations, the metallicities of Gl 676A and HIP 12961 are 0.18 and  $-0.07$ . Both values are above the  $[\text{Fe}/\text{H}] = -0.17$  average metallicity for the solar neighborhood in the Schlaufman & Laughlin (2010) metallicity scale, the latter very significantly so. The two new planets therefore clearly reinforce the incipient trend, and help suggest that more massive planets are found around more metal-rich M-dwarfs.

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**Fig. 4.** *Top panel:* HARPS radial velocities of Gl 676A as a function of orbital phase, after subtraction of adjusted linear drift and overlaid with the adjusted Keplerian orbit. *Middle panel:* residual of the HARPS radial from the adjusted orbit and linear drift, as a function of time. *Bottom Panel:* Lomb-Scargle periodogram of the residuals. The horizontal lines mark false alarm probabilities equivalent to 1 and 2 sigma significance levels for Gaussian noise.

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