Astronomy
&
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The HARPS survey for southern extra-solar planets[★]

II. A 14 Earth-masses exoplanet around μ Arae

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Abstract. In this letter we present the discovery of a very light planetary companion to the star μ Ara (HD 160691). The planet orbits its host once every 9.5 days, and induces a sinusoidal radial velocity signal with a semi-amplitude of 4.1 m s^{-1}, the smallest Doppler amplitude detected so far. These values imply a mass of $m_2 \sin i = 14$ $M_\oplus$ (Earth-masses). This detection represents the discovery of a planet with a mass slightly smaller than that of Uranus, the smallest "ice giant" in our Solar System. Whether this planet can be considered an ice giant or a super-earth planet is discussed in the context of the core-accretion and migration models.

Key words. stars: individual: HD 160691 – planetary systems – techniques: radial velocities

1. Introduction

The discovery of giant planets around other solar-type stars has opened the way to a new era of planetary research. The new worlds present a wide variety of orbital characteristics and minimum masses, and 9 years after the first announcement (Mayor & Queloz 1995), some of their properties are still defying the theories of planetary formation. The increasing number of known systems is, however, giving the possibility to explore their properties from a statistical point of view (e.g. Santos et al. 2001; Zucker & Mazeh 2002; Udry et al. 2003; Eggenberger et al. 2004), and the observational and theoretical approaches are now starting to converge (e.g. Trilling et al. 2002; Alibert et al. 2004; Ida & Lin 2004a).

Recently, with the installation of the new HARPS spectrograph (Pepe et al. 2002) at the 3.6-m ESO telescope (La Silla, Chile) a significant quantitative advance has been possible. This state of the art instrument is capable of attaining a precision better than 1 m s^{-1}. After only a few weeks of operation,

it has discovered a first "hot-jupiter" (Pepe et al. 2004) orbiting the K dwarf HD 330075. The level of precision in radial-velocity measurements achieved with HARPS gives now, for the first time, the possibility of lowering significantly the detection limit to the "few-earth-mass" regime, provided that the signal induced by stellar oscillations can be reduced with the use of an appropriate observing strategy (Bouchy et al., in preparation).

In this letter we present the discovery of a $\sim$14-$M_\oplus$ short period ($P \sim 9.5$ days) extra-solar planet orbiting the star μ Ara, a star that was already known to be orbited by a longer period giant planet (Butler et al. 2001). Together with the very low mass companion to 55 Cnc (McArthur et al. 2004), these are the only two sub-neptunian planets discovered to date. They are suspected to be earth-like rocky planets, orbiting solar-type stars.

2. Stellar characteristics of μ Ara

μ Ara (HD 160691, HR 6585, GJ 691) is a nearby $V = 5.12$ mag southern G5V star in the constellation Ara, the Altar, and according to the Hipparcos catalog (ESA 1997), it has a

parallax of 65.5 ± 0.8 mas, which implies a distance from the Sun of 15.3 pc, and an absolute magnitude of $M_v = 4.20$. Its color index $B - V$ is 0.694.

From a HARPS spectrum with a S/N ratio of the order of ~1000 (average of 275 individual spectra), we have derived the stellar parameters for μ Ara using a fully spectroscopic analysis (Santos et al. 2004). The resulting parameters ($T_{\rm eff}$, $\log g$, V_t, [Fe/H]) = (5813 ± 40 K, 4.25 ± 0.07 dex, 1.30 ± 0.05 km s^{-1}, $+0.32 \pm 0.05$ dex), are in almost perfect agreement with the values published in Santos et al. (2004), Bensby et al. (2004), and Laws et al. (2003). The surface gravity derived using the Hipparcos parallax and an effective temperature of 5800 K is 4.25 dex (see e.g. Santos et al. 2004).

Using the temperature, [Fe/H], absolute magnitude and bolometric correction (Flower 1996), we derived a stellar mass of 1.10 ± 0.05 $M_\odot$ for μ Ara, from an interpolation of the theoretical isochrones of Schaerer et al. (1993). This is in excellent agreement with the 1.08 and 1.14 $M_\odot$ derived by Butler et al. (2001) and Laws et al. (2003), respectively. Preliminary results from the asteroseismology analysis are also in excellent agreement with these values (Bazot et al., in preparation).

From the width of the CORALIE Cross-Correlation Function (CCF) we have computed a projected rotational velocity of 2.4 km s^{-1} for μ Ara (Santos et al. 2002). This value is in agreement with the low chromospheric activity level of the star, $\log R'_{\rm HK} = -5.034 \pm 0.006$, obtained from the HARPS spectra. Similar values of -5.02 were obtained both from the CORALIE data (Santos et al. 2000) and by Henry et al. (1996) at different epochs. The inactivity of this star is further supported by its low (and non-variable) X-ray luminosity (Marino 2002), as well as by the lack of significant photometric variation in the Hipparcos data (ESA 1997).

From the observed value of $\log R'_{\rm HK}$ we can infer an age above ~2 Gyr (Pace & Pasquini 2004) and a rotational period of ~31 days (Noyes et al. 1984). This age is compatible with the 4.5 Gyr obtained from an interpolation of theoretical isochrones (e.g. Laws et al. 2003), and with the upper value for the lithium abundance $\log \epsilon({\rm Li}) < 0.86$ dex derived by Israelian et al. (2004) for this dwarf.

3. Radial velocities

In June 2004, μ Ara was intensively measured over 8 consecutive nights with the HARPS spectrograph as part of an asteroseismology program (Bouchy et al., in preparation). During each night, we obtained more than 250 spectra of this star, from which we derived accurate radial velocities. The average radial velocity for each night was then computed from a weighted average of each individual value, its precision being limited by the uncertainty in the wavelength calibration[1].

The main motivation of this program was to study the possibility that the high metal content of the planet-host stars (e.g. Gonzalez 1998; Santos et al. 2001, 2004, and references therein) is due to the engulfment of metal rich planetary material into their convective envelopes. Although current

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[1] The nightly average of the HARPS radial velocities will be available in electronic form at CDS.

Table 1. Orbital elements of the fitted 9.5-days period orbit and main planetary properties.

P	9.55 ± 0.03	[d]
T	2453168.94 ± 0.05	[d]
e	0.00 ± 0.02	
ω	4 ± 2	[deg]
K_1	4.1 ± 0.2	[m s^{-1}]
$a_1 \sin i$	0.5396	[Gm]
$f_1(m)$	0.6869	[10^{-13} $M_\odot$]
σ(O–C)	0.9	[m s^{-1}]
N	24	
$m_2 \sin i$	14	[$M_\oplus$]
a	0.09	[AU]
$T_{\rm eq}$	~900*	[K]

* Equilibrium temperature computed with an albedo of 0.35.

studies seem to favor that the observed "excess" metallicity reflects a higher metal content of the cloud of gas and dust that gave origin to the star and planetary system, recent results have suggested that this matter may still be unsettled (e.g. Vauclair 2004). The asteroseismology technique provides us with a good tool to possibly solve this problem. As shown by Bazot & Vauclair (2004), precise stellar oscillation measurements may be able to determine if there is some metallicity gradient in the stellar interior, that could be a hint of strong stellar "pollution" events. The results of the asteroseismology campaign will be presented in Bouchy et al. (in preparation) and Bazot et al. (in preparation).

A first analysis of the data revealed what could be a periodic variation with an amplitude of about 4 m s^{-1} (see Figs. 1 and 2). As part of the HARPS GTO program, this star was then closely followed from July 14th to August 19th 2004 (16 radial-velocity measurements were obtained). Each night the radial velocity was measured from the average of about 15 consecutive independent radial velocity estimates (computed from different spectra) taken during a period of ~20 min. This methodology makes it possible to average the radial-velocity variations due to stellar oscillations (Mayor et al. 2003) – see also Bouchy et al. (in preparation). As seen in Fig. 1, the measurements done during the first 8 nights (when the star was followed during the whole night) have a considerable lower rms around the best Keplerian fit than the following measurements. This scatter results from the photon noise error (~20 cm s^{-1}), the calibration uncertainty (~40 cm s^{-1}), and from the stellar noise (~80 cm s^{-1}) that is not completely averaged on the nights with only 15 radial velocity measurements (Bouchy et al., in preparation).

μ Ara was previously announced to harbor a giant planet in a long period (~740 days) orbit (Butler et al. 2001). This orbital solution has since been updated by Jones et al. (2002), who found that the residuals of the radial-velocity planetary fit followed a long term trend, due to the presence of a second body in the system.

In Fig. 3 we plot the radial-velocity measurements of μ Ara obtained during the last 6 years using three different instruments (see figure caption), as well as the best 2-Keplerian fit.
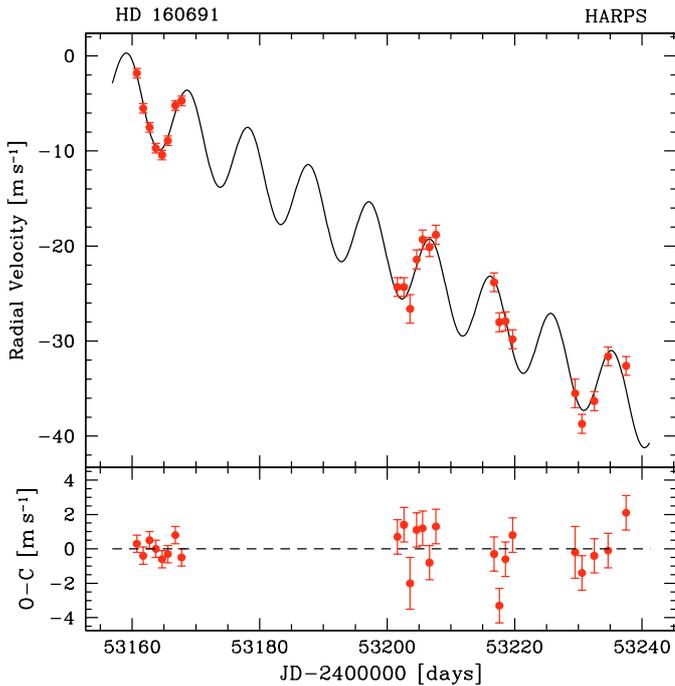
Fig. 1. HARPS radial-velocity measurements of μ Ara as a function of time. The filled line represents the best fit to the data, obtained with the sum of a Keplerian function and a linear trend, representing the effect of the long period companions to the system. The residuals of the fit, with an rms of only 0.9 m s^{-1}, are shown in the lower panel.

The orbit of the ~740-day period planet (actually with a period of ~660 days) is confirmed. However, the orbital parameters of the second (longer period) companion are not well constrained; we find a strong degeneracy between the derived orbital period and the value of the orbital excentricity, making it possible to fit the data with the former parameter varying between ~3000 and 10 000 days. Although not precisely determined, the mass of this companion remains probably in the planet regime. Despite of the still unconstrained long period of this outer companion, some stability studies of the system has been discussed (e.g. Gozdziewski et al. 2003).

4. A 9.5-days period planet with 14 Earth-masses

In Figs. 1 and 2 we present the HARPS radial-velocity measurements of μ Ara as a function of time. In this figure, the curve represents the best fit to the data, obtained with the sum of a Keplerian function and a linear trend. The derived slope of this trend is in agreement with the expected effect due to the longer period companions (see Fig. 3).

The analysis of the radial velocity measurements reveals a variation with a period of 9.5 days, and a semi-amplitude of about 4 m s^{-1}. These values can be explained by the presence of a $m_2 \sin i = 14\,M_\oplus$ planet orbiting μ Ara in a circular orbit.

The residuals around the best fit to the HARPS data are flat, with a rms of only of 0.9 m s^{-1}. This rms decreases to the calibration level (0.43 m s^{-1}) for the first 8 nights, attesting the incredible precision of this instrument. Despite the low amplitude of the radial velocity signal, the false alarm
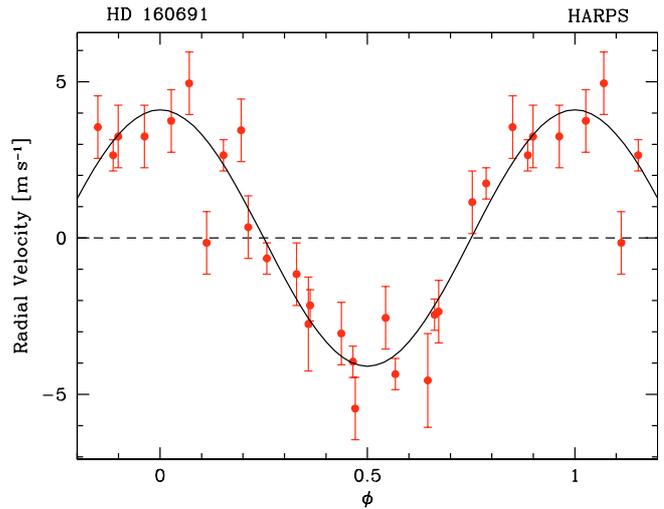

Fig. 2. Phase-folded radial-velocity measurements of μ Ara after subtraction of the linear trend shown in the upper panel of Fig. 1. In both panels the error bars represent the rms around the weighted average of the individual measurements for a given night.
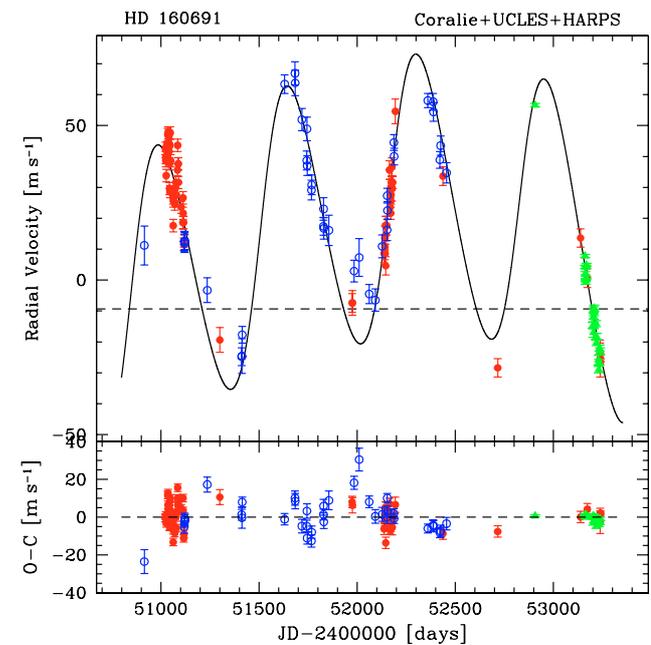

Fig. 3. Radial velocity measurements of μ Ara obtained during the past 6 years with the CORALIE (dots) and HARPS spectrographs (open triangles), and by Jones et al. (2002) (open circles). The curve represents the best 2-body Keplerian fit to the data. In the lower panel we present the rms around the fit. For the longer period Keplerian fit, the eccentricity was fixed to a value of 0.2.

probability that it is due to random noise is lower than 1%, as derived through a Monte-Carlo simulation.

From the stellar luminosity and effective temperature we can derive a radius of ~1.32 solar radii for μ Ara. Combined with the rotational period of 31 days (see Sect. 2), this implies a rotational velocity of the order of 2.2 km s^{-1} for μ Ara, close to the measured value $v \sin i = 2.4$ km s^{-1}. Supposing that the orbital plane is perpendicular to the stellar rotation axis, this means that the orbital inclination $\sin i$ is close to unity, and that

the observed minimum mass for the planet is not very different from its real mass.

Using the HARPS spectra we have derived both an activity index, based on Ca II H and K lines, and the bisector of the cross-correlation function from the individual spectra. No correlation is found between these quantities and the radial velocities within the measurement precision. Given the very low activity level of μ Ara and the inferred rotational period of ~30 days, it is very unlikely that rotational modulation is capable of producing the observed stable periodic radial-velocity variation. Furthermore, to have a rotational period of 9.5 days, this star would have to rotate at about 7 km s^{-1}. Such a rotational velocity would imply a much younger age for μ Ara, not compatible with its low level of activity.

The presence of a 14 $M_\oplus$ planet around μ Ara thus remains the only credible explanation for the observed 9.5-days period radial-velocity variation.

5. Discussion

As current planetary formation models are still far from being able to account for all the amazing diversity observed amongst the exoplanets discovered thus far, we can only speculate on the true nature of the present object.

First, given its location and the characteristics of the central star, it is unlikely that this object was in fact a much more massive giant planet which has lost a large fraction of its envelope over its lifetime. This is supported by the fact that more massive planets exist orbiting much closer to stars with similar characteristics and by calculations by Baraffe et al. (2004) and Lecavelier des Etangs et al. (2004) which show that only planets significantly less massive than Jupiter would evaporate at 0.09 AU. Except if outward migration has occurred, we conclude that the mass of this object has always remained small.

To understand the consequences of this, it is necessary to recall that in the current paradigm of giant planet formation, a core is formed first through the accretion of solid planetesimals. Once this core reaches a critical mass (m_{crit}), accretion of gas in a runaway fashion becomes possible and the mass of the planet increases rapidly (e.g. Ida & Lin 2004b). This therefore implies that the current object has never reached the critical mass, for otherwise the planet would have become much more massive. Furthermore, recent giant planet formation models including disk evolution and migration (Alibert et al. 2004) have shown that these effects greatly shorten the formation time. Hence, it is unlikely that the planet has migrated over large distances before reaching its present location. It was thus probably formed inside the ice radius (~3.2 AU – Ida & Lin 2004a), and its composition should be dominated by rocky (telluric) material. We note that the high [Fe/H] of μ Ara makes this case possible (Ida & Lin 2004a). Curiously, with 14 $M_\oplus$ and $a = 0.09$ AU, this planet is near the borderline of the mass-period desert defined by Ida & Lin (2004b), where no planets are supposed to exist.

The above considerations lead us towards the following scenario for the formation of the present planetary system. The more massive planet, with the present ~660 days period orbit, begins to form first and migrates inwards while growing in mass. Towards the end of the lifetime of the disk, the smaller planet is formed inside the orbit of the larger one, probably at a distance not exceeding 3 AU. Thus, we expect this object to have a massive, essentially rocky core (as opposed to icy), surrounded by a gaseous envelope with ~5–10% of its mass. It therefore probably qualifies as a super-Earth and not as a failed ice-giant.

The discovery of this extremely low-mass planet represents a new benchmark for planet surveys, and demonstrates the ability of instruments like HARPS to detect telluric planets with just a few times the mass of the Earth. In the future these detections will give the possibility to study the low end of the planetary-mass distribution. This kind of planets may be relatively common, as according to recent simulations (Ida & Lin 2004a), very low-mass planets may be more frequent than the previously found giant worlds. This is further supported by the recent detection of a first neptunian planet in a short period orbit around 55 Cnc (McArthur et al. 2004)[2]. Such planets will be preferential targets for space missions like the photometric satellites COROT and Kepler. Furthermore, the discovery of such low mass planets around stars that have at least one more giant exoplanet, makes of these systems very interesting cases to understand the processes of planetary formation and evolution.

References

Alibert, Y., Mordasini, C., & Benz, W. 2004, A&A, 417, L25

Baraffe, I., Selsis, F., Chabrier, G., et al. 2004, A&A, 419, L13

Bazot, M., & Vauclair, S. 2004, A&A, submitted [arXiv:astro-ph/0407544]

Bensby, T., Feltzing, S., & Lundström, I. 2003, A&A, 410, 527

Butler, R. P., Vogt, S., Marcy, G., et al. 2004, ApJ, in press

Butler, R. P., Tinney, C. G., Marcy, G., et al. 2001, ApJ, 555, 410

Eggenberger, A., Udry, S., & Mayor, M. 2004, A&A, 417, 353

ESA 1997, The Hipparcos and Tycho Cat., ESA SP-1200

Flower, P. J. 1996, ApJ, 469, 355

Gonzalez, G. 1998, A&A, 334, 221

Gozdziewski, K., Konacki, M., & Maciejewski, A. 2003, ApJ, 594, 1019

Henry, T. J., Soderblom, D. R., Donahue, R. A., & Baliunas, S. L. 1996, AJ, 111, 439

Ida, S., & Lin, D. N. C. 2004a, ApJ, in press [arXiv:astro-ph/0408019]

Ida, S., & Lin, D. N. C. 2004b, ApJ, 604, 388

Israelian, G., Santos, N. C., Mayor, M., & Rebolo, R. 2004, A&A, 414, 601

Jones, H. R. A., Butler, R. P., Marcy, G. W., et al. 2002, MNRAS, 337, 1170

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[2] A companion to the M-dwarf GJ 436 with a minimum mass $m_2 \sin i = 21\ M_\oplus$ was also announced by Butler et al. (2004) after the submission of the current letter.

Laws, C., Gonzalez, G., Walker, K., et al. 2003, AJ, 125, 2664

Lecavelier des Etangs, A., Vidal-Madjar, A., McConnell, J. C., & Hébrard, G. 2004, A&A, 418, L1

Marino, A., Micela, G., Peres, G., & Sciortino, S. 2002, A&A, 383, 210

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

Mayor, M., & Queloz, D. 1995, Nature, 378, 355

McArthur, B., Endl, M., Cochran, W., et al. 2004, ApJ, in press

Noyes, R. W., Hartmann, L. W., Baliunas, S. L., et al. 1984, ApJ, 279, 763

Pace, G., & Pasquini, L. 2004, A&A, in press
[arXiv:astro-ph/0406651]

Pepe, F., Mayor, M., Rupprecht, G., et al. 2002, The ESO Messenger, 110, 9

Pepe, F., Mayor, M., Queloz, D., et al. 2004, A&A, 423, 385

Santos, N. C., Mayor, M., Naef, D., et al. 2000, A&A, 361, 265

Santos, N. C., Israelian, G., & Mayor, M. 2001, A&A, 373, 1019

Santos, N. C., Mayor, M., Naef, D., et al. 2002, A&A, 392, 215

Santos, N. C., Israelian, G., & Mayor, M. 2004, A&A, 415, 1153

Schaerer, D., Charbonnel, C., Meynet, G., Maeder, A., & Schaller, G. 1993, A&AS, 102, 339

Trilling, D., Lunine, J., & Benz, W. 2002, A&A, 394, 241

Udry, S., Mayor, M., & Santos, N. C. 2003, A&A, 407, 369

Vauclair, S. 2004, ApJ, 605, 874

Zucker, S., & Mazeh, T. 2002, ApJ, 568, L113

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