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Letter to the Editor

Three planetary companions around M67 stars. ⋆

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ABSTRACT

For the past six years we have carried out a search for massive planets around main sequence and evolved stars in the open cluster (OC) M67, using radial velocity (RV) measurements obtained with HARPS at ESO (La Silla), SOPHIE at OHP and HRS at HET. Additional RV data come from CORALIE at the Euler Swiss Telescope. We aim to perform a long-term study on giant planet formation in open clusters and determine how it depends on stellar mass and chemical composition.

We report the detection of three new extrasolar planets: two in orbit around the two G dwarfs YBP1194 and YBP1514, and one around the evolved star S364. The orbital solution for YBP1194 yields a period of 6.9 days, an eccentricity of 0.24, and a minimum mass of 0.34 $M_{\rm Jup}$. YBP1514 shows periodic RV variations of 5.1 days, a minimum mass of 0.40 $M_{\rm Jup}$, and an eccentricity of 0.39. The best Keplerian solution for S364 yields a period of 121.7 days, an eccentricity of 0.35 and a minimum mass of 1.54 $M_{\rm Jup}$. An analysis of Hα core flux measurements as well as of the line bisectors spans revealed no correlation with the RV periods, indicating that the RV variations are best explained by the presence of a planetary companion. Remarkably, YBP1194 is one of the best solar twins identified so far, and YBP1194b is the first planet found around a solar twin that belongs to a stellar cluster. In contrast with early reports and in agreement with recent findings, our results show that massive planets around stars of open clusters are as frequent as those around field stars.

Key words. Exoplanets – Open clusters and associations: individual: M67 – Stars: late-type – Techniques: radial velocities

1. Introduction

In 2008 we began monitoring radial velocities (RVs) of a sample of main sequence and giant stars in the open cluster (OC) M67, to detect signatures of giant planets around their parent stars. An overview of the sample and of our first results is reported in Pasquini et al. (2012). The goal of this campaign is to study the formation of giant planets in OCs to understand whether a different environment, such as a rich cluster like M67, might affect the planet formation process, the frequency, and the evolution of planetary systems with respect to field stars. In addition, searching for planets in OCs enables us to study the dependence of planet formation on stellar mass and to compare the chemical composition of stars with and without planets in detail. Stars in OCs share age and chemical composition (Randich et al. 2005), therefore it is possible to strictly control the sample and to limit the space of parameters in a better way than when studying field stars. To address these questions we started a search for planets around stars of the OC M67. This cluster has solar age (3.5-4.8 Gyr; Yadav et al. 2008) and solar metallicity (+0.03±0.01 dex; Randich et al. 2006). In this letter, we present the RV data obtained for the stars YBP1194, YBP1514, and S364 that reveal the presence of Jovian-mass companions.

2. Stellar characteristics

The three stars belong to the M67 sample presented in Pasquini et al. (2012) with a proper motion membership probability higher than 60% according to Yadav et al. (2008) and Sanders (1977) (see online material). The basic stellar parameters (V, $B-V$, $T_{\rm eff}$, $\log g$ and [Fe/H]) with their uncertainties were adopted from the literature. Considering a distance modulus of 9.63±0.05 (Pasquini et al. 2008) and a reddening of E(B-V)=0.041±0.004 (Taylor 2007), stellar masses and radii were estimated using the 4 Gyr theoretical isochrones from Pietrinferni et al. (2004) and Girardi et al. (2000). The parameters derived from isochrone fitting are comparable, within the errors, with the values adopted from the literature. The main characteristics of the three host stars are listed in Table 1. We note that the errors on these values do not include all potential systematics (see online material).

YBP1194 is a G5V star, described by Pasquini et al. (2008) as one of the five best solar analogs in their sample. A detailed spec-

⋆ Based on observations collected at the ESO 3.6m telescope (La Silla), at the 1.93m telescope of the Observatoire de Haute-Provence (OHP) and at the Hobby Eberly Telescope (HET).

Table 1. Stellar parameters of the three M67 stars hosting planets

Parameters	YBP1194	YBP1514	SAND364
α (J2000)	08:51:00.81	08:51:00.77	08:49:56.82
δ (J2000)	+11:48:52.76	+11:53:11.51	+11:41:33.00
Spec.type	G5V	G5V	K3III
m_V [mag]	14.6[a]	14.77[a]	9.8[b]
$B-V$ [mag]	0.626[a]	0.680[a]	1.360[b]
$M\star$ [$M_\odot$]	1.01±0.02[c]	0.96±0.01[d]	1.35±0.05[d]
$R\star$ [$R_\odot$]	0.99±0.02[d]	0.89±0.02[d]	21.8±0.7[d]
$\log g$ [cgs]	4.44±0.035[c]	4.57±0.05[e]	2.20±0.06[f]
$T_{\rm eff}$ [K]	5780±27[c]	5725±45[e]	4284±9[f]
[Fe/H] [dex]	0.023±0.015[c]	0.03±0.05[e]	−0.02±0.04[f]

Notes. [a] Yadav et al. (2008). [b] Montgomery et al. (1993). [c] Önehag et al. (2011). [d] Pietrinferni et al. (2004) and Girardi et al. (2000). [e] Smolinski et al. (2011) and Lee et al. (2008). [f] Wu et al. (2011).

troscopic analysis (Önehag et al. 2011) has confirmed the star as one of the best-known solar-twins.
YBP1514 also is a G5 main sequence star. We adopted the atmospheric parameters obtained by Smolinski et al. (2011), who used spectroscopic and photometric data from the original Sloan Digital Sky Survey (SDSS-I) and its first extension (SDSS-II/SEGUE). These values are consistent, within the errors, with what has been found in previous work on the same data by Lee et al. (2008) and in the study of Pasquini et al. (2008).
S364 (MMJ6470) is an evolved K3 giant star. The stellar parameters, summarized in Table 1, are taken from Wu et al. (2011). We derived its mass and radius by isochrone fitting (Pietrinferni et al. 2004).

3. Radial velocities and orbital solutions

The RV measurements were obtained using the HARPS spectrograph (Mayor et al. 2003) at the ESO 3.6m telescope in high-efficiency mode (with R=90000 and a spectral range of 378-691 nm); the SOPHIE spectrograph (Bouchy & Sophie Team 2006) at the OHP 1.93 m telescope in high-efficiency mode (with R=40000 and a spectral range of 387-694 nm), and the HRS spectrograph (Tull 1998) at the Hobby Eberly Telescope (with R=60000 and a wavelength range of 407.6-787.5 nm). In addition, we gathered RV data points for giant stars observed between 2003 and 2005 (Lovis & Mayor 2007) with the CORALIE spectrograph at the 1.2 m Euler Swiss telescope. HARPS and SOPHIE are provided with a similar automatic pipeline to extract the spectra from the detector images and to cross-correlate them with a G2-type mask obtained from the Sun spectra. Radial velocities are derived by fitting each resulting cross-correlation function (CCF) with a Gaussian (Baranne et al. 1996; Pepe et al. 2002). For the HRS, the radial velocities were computed using a series of dedicated routines based on IRAF and cross-correlating the spectra with a G2 star template (Cappetta et al. 2012). All the observations for each star were corrected to the zero point of HARPS, as explained in Pasquini et al. (2012), and were analyzed together. Two additional corrections were applied to the SOPHIE data, to take into account the modification of the fiber link in June 2011 (Perruchot et al. 2011) and the low S/N ratio of the observations. For the first, we calculated the offset between RV values of our stellar standard (HD32923) before and after the change of the optical setup. For the second, we corrected our spectra using eq.(1) in Santerne et al. (2012). We studied the RV variations of our target stars by computing the Lomb-Scargle

Table 2. Orbital parameters of the planetary companions. P: period, T: time at periastron passage, e: eccentricity, ω: argument of periastron, K: semi-amplitude of RV curve, $m \sin i$: planetary minimum mass, γ: average radial velocity, σ(O-C): dispersion of Keplerian fit residuals.

Parameters	YBP1194	YBP1514	SAND364
P [days]	6.958±0.001	5.118±0.001	121.710±0.305
T [JD]	2455978.8±0.5	2455986.3±0.3	2456240.9±3.7
e	0.24±0.08	0.39±0.17	0.35±0.08
ω [deg]	98.62±25.68	327.49±16.05	273.51±12.81
K [m s^{-1}]	37.72±4.27	52.29 ±10.39	67.42±5.85
$m \sin i$ [$M_{\rm Jup}$]	0.34±0.05	0.40±0.11	1.54±0.24
γ [km s^{-1}]	34.184±0.006	34.057±0.017	33.217±0.018
σ(O-C) [m s^{-1}]	11.55	14.6	15.0

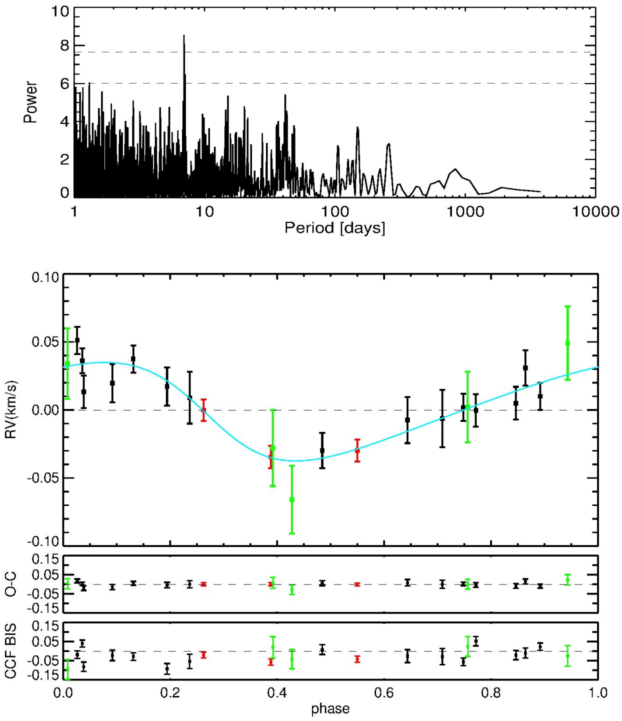

Fig. 1. Top: Lomb-Scargle periodogram for YBP1194. The dashed lines correspond to 5% and 1% false-alarm probabilities, calculated according to Horne & Baliunas (1986) and white noise simulations. Bottom: phased RV measurements and Keplerian best fit, best-fit residuals, and bisector variation for YBP1194. Black dots: HARPS measurements, red dots: SOPHIE measurements, green dots: HRS measurements.

periodogram (Scargle 1982; Horne & Baliunas 1986) and by using a Levenberg-Marquardt analysis (Wright & Howard 2009, RVLIN) to fit Keplerian orbits to the radial velocity data. The orbital solutions were independently checked using the Yorbit program (Segransan et al. 2013 in prep.). For each case we verified that the RVs did not correlate with the bisector span of the CCF (calculated following Queloz et al. (2001)) or with the FWHM of the CCF. All the RV data for each star are available in the online material.

YBP1194
We have acquired 23 RV measurements since 2008. Fifteen were obtained with HARPS with a typical S/N of 10 (per pixel at 550 nm), leading to a mean measurement uncertainty of 13 m s^{-1}including calibration errors. Eight additional RV measurements were obtained with SOPHIE and HRS with mean measurement uncertainties of 9.0 m s^{-1}and 26.0 m s^{-1}. A clear 6.9-day periodic signal can be seen in the periodogram (see

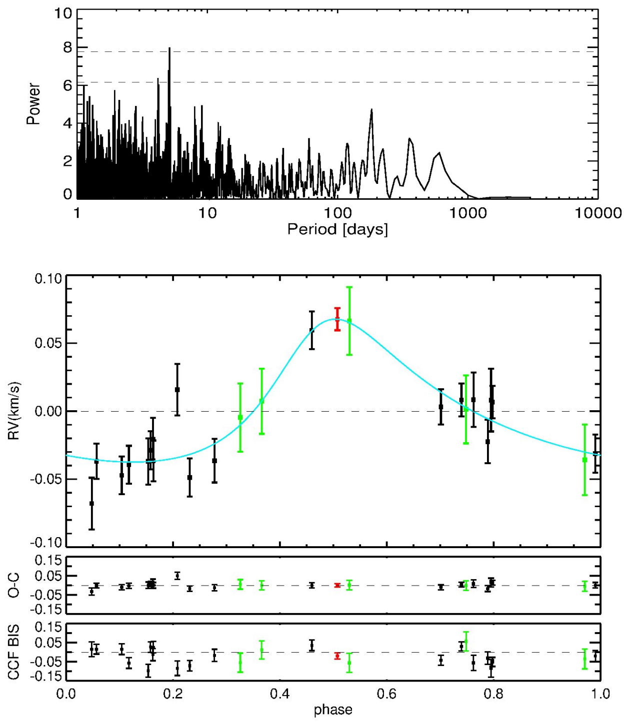

Fig. 2. Top: Lomb-Scargle periodogram for YBP1514. Bottom: phased RV measurements and Keplerian best fit, best-fit residuals, and bisector variation for YBP1514. Same symbols as in Fig.1.

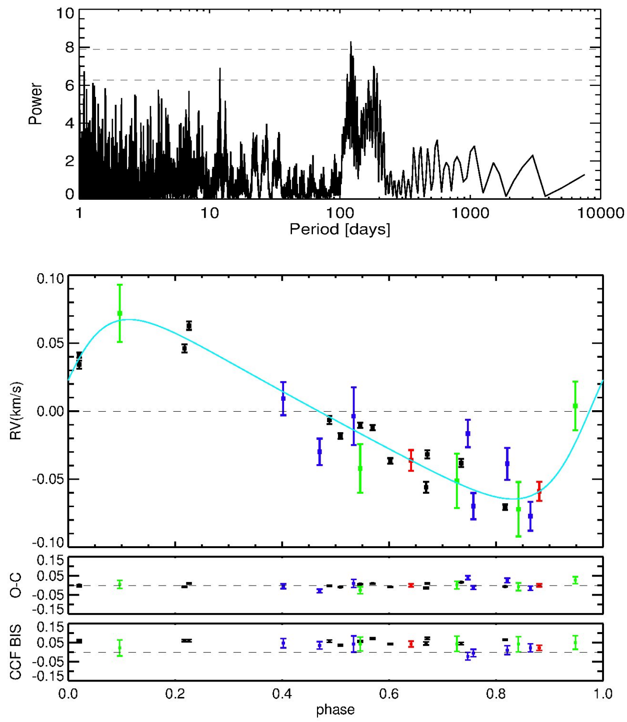

Fig. 3. Top: Lomb-Scargle periodogram for S364. Bottom: phased RV measurements and Keplerian best fit, best-fit residuals, and bisector variation for S364. Same symbols as in Fig.1.

fig.1 top) with its one-year and two-year aliases on both sides (at 6.7 d and 7.03 d). A single-Keplerian model was adjusted to the data (fig.1 bottom). The resulting orbital parameters for the planet candidate are reported in Table 2. The residuals' dispersion is σ(O-C)= 11.55 $\mathrm{m\,s^{-1}}$, comparable with the mean measurement accuracy (~15 $\mathrm{m\,s^{-1}}$), and the periodogram of the residuals does not show significant power excess, although structures are present.

YBP1514
Twenty-five RV measurements have been obtained for YBP1514 since 2009: 19 with HARPS, the others with HRS and SOPHIE. The typical S/N is ~10 and the measurement uncertainty is ~15 $\mathrm{m\,s^{-1}}$for HARPS, ~25 $\mathrm{m\,s^{-1}}$for HRS, and ~10 $\mathrm{m\,s^{-1}}$for SOPHIE. A significant peak is present in the periodogram at 5.11 days (fig.2 top), together with its one-year alias at 5.04 days. We fitted a single-planet Keplerian orbit corresponding to the period P= 5.11 days (fig.2 bottom). The orbital parameters resulting from this fit are listed in Table 2. Assuming a mass of 0.96 $M_{\odot}$ for the host star, we computed a minimum mass for the companion of 0.40±0.11 $M_{\rm Jup}$. The residuals to the fitted orbit have a dispersion of σ(O-C)= 14.6 $\mathrm{m\,s^{-1}}$, within the mean measurement uncertainty, and show no significant periodicity.

S364
We collected 20 radial velocity measurements of S364 in about four years with HARPS, HRS, and SOPHIE. The average RV uncertainty is ~3.0 $\mathrm{m\,s^{-1}}$for HARPS, ~7.0 $\mathrm{m\,s^{-1}}$for SOPHIE and ~20 $\mathrm{m\,s^{-1}}$for HRS. Seven additional RV measurements were obtained with CORALIE between 2003 and 2005, with a mean measurement uncertainty of ~12 $\mathrm{m\,s^{-1}}$. The periodogram of the observed data is shown in fig.3 (top) and indicates an excess of power at ≈121.7 days. The other clearly visible peak at 182 days is the one-year alias of the planetary signal at P=121.7 days. It disappears in the periodogram of residuals, which no longer shows any signal. We fitted a single-planet Keplerian orbit to this signal (fig. 3 bottom) and found an orbital solution whose parameters are reported in Table 2. The residuals to the fitted orbit show a level of variation of σ =16.0 $\mathrm{m\,s^{-1}}$, higher than the estimated accuracy, but the periodogram of the residuals does not reveal significant peaks.

4. Discussion and prospects

We have presented new results from our planet-search campaign in the OC M67. Our measurements reveal that Y1194, Y1514, and S364 host planets.

To rule out activity-related rotational modulation as the cause of the RV variations in our object data, we investigated chromospheric activity in these stars by measuring the variations of the core of Hα with respect to the continuum. The low S/N ratio of our observations does not provide sufficient signal in the region of the more sensitive Ca II H and K lines. We followed a method similar to the one described in Pasquini & Pallavicini (1991). All the targets exhibit a very low level of activity: S364 shows a variability in Hα of 2%, YBP1514 and YBP1194 of 3% without significant periodicity. In addition, the M67 stars have a very low level of chromospheric activity (Pace & Pasquini (2004): $< F'_K >\sim 0.5 \cdot 10^6$ $\mathrm{erg\,cm^{-2}\,s^{-1}}$ for M67 compared with $< F'_K >\sim 2.1 \cdot 10^6$ $\mathrm{erg\,cm^{-2}\,s^{-1}}$ for the Hyades), which is not compatible with generating the high RV variations we observe. Therefore, rotationally modulated RV variations for the dwarfs in M67 are certainly not a concern. The remote possibility that these stars are short-period binaries seen pole-on can also be excluded, because they are very active, and will show enhanced Hα cores and strong X-ray emission, which has not been observed for these stars (van den Berg et al. 2004). The fact that these stars are of solar age and that our research is focused on finding giant planets with an expected RV variability of tens of $\mathrm{m\,s^{-1}}$makes the contamination by activity irrelevant.

It is remarkable that Y1194 is one of the best-known solar twins. This star together with Y1514, S364, and the other M67 targets will be suitable for a detailed differential abundance analysis to compare the chemical composition of stars with and without giant planets.

All the orbital solutions show nonzero eccentricity, but this is also common among planets found around field stars. Quinn et al. (2013) explained that hot-Jupiters in OCs with nonzero eccentric orbits and circularization time-scales t_{circ} longer than the system age, might provide an observational signature of the hot-Jupiter migration process via planet-planet scattering. We evaluated t_{circ} for the eccentric orbits of YBP1194 and YBP1514. Assuming a tidal quality factor $6 \times 10^4 < Q_p < 2 \times 10^6$, we calculated $409Myr < t_{circ} < 13.6Gyr$ for YBP1194 and $220Myr < t_{circ} < 6.9Gyr$ for YBP1514 (see Quinn et al. (2013) for details). Given the solar age of M67 and the wide range of possible t_{circ}, reflecting the choice of the Q_p and the estimation of the planetary radius, no firm conclusion can be drawn for the origin of the eccentric short-period orbits of these stars. Moreover, further investigations and more RV data are needed to better constrain the eccentricities of these objects (see Pont et al. 2011).

The planet around the giant S364 belongs to the low-populated region of periods between ∼10 and ∼200 days and is one of the shortest periods found around evolved stars.

When we examine the current distribution of the Jupiter-mass planets for RV surveys around FGK stars we find an exoplanet host-rate higher than 10% for planets with a period of up to a few years and 1.20±0.38% at solar metallicity, for very close-in hot-Jupiters with a period shorter than ten days (Cumming et al. 2008; Mayor et al. 2011; Wright et al. 2012). This rate around field stars has been in contrast to the lack of detected planets in both open and globular cluster for several years. Before 2012, the detections were limited to a long-period giant planet around one of the Hyades clump giants (Sato et al. 2007) and to a substellar-mass object in NGC2423 (Lovis & Mayor 2007). No evidence of short-period giant planets has been presented in the study of Paulson et al. (2004) around main-sequence stars of the Hyades, or in several transit campaigns (Bramich et al. 2005; Mochejska et al. 2005, 2006; Pepper et al. 2008; Hartman et al. 2009). These triggered the hypothesis that the frequency of planet-hosting stars in clusters is lower than in the field. To explain the dichotomy between field and cluster stars, it has been suggested that the cluster environment might have a significant impact on the disk-mass distribution. Eisner et al. (2008), studying disks around stars in the Orion Nebula Cluster (ONC), proposed that most of these stars do not posses sufficient mass in the disk to form Jupiter-mass planets or to support an eventual inward migration. Other scenarios may be attributed to post-formation dynamics, in particular to the influence of close stellar encounters (Spurzem et al. 2009; Bonnell et al. 2001) or to tidal evolution of the hot-Jupiters (Debes & Jackson 2010) in the dense cluster environment. van Saders & Gaudi (2011), in contrast, found no evidence in support of a fundamental difference in the short-period planet population between clusters and field stars, and attributed the nondetection of planets in transit surveys to the inadequate number of stars surveyed. This seems to be confirmed by the recent results. Indeed, we can list the discovery of two hot-Jupiters in the Praesepe open cluster in 2012 (Quinn et al. 2012) and of two sub-Neptune planets in the cluster NGC6811 as part of The Kepler Cluster Study (Meibom et al. 2013), the new announcement of a hot-Jupiter in the Hyades (Quinn et al. 2013) and now the detection in M67 of three Jupiter-mass planets presented in this work. Quinn et al. (2012) obtained a lower limit on the hot-Jupiter frequency in Praesepe of $3.8^{+5.0}_{-2.4}\%$, which is consistent with that of field stars considering the enriched metallicity of this cluster. Meibom et al. (2013) have found the same properties and frequency of low-mass planets in open clusters as around field stars. In our case, for short-period giant planets we derived a frequency of $2^{+3.0}_{-1.5}\%$ (errors computed according to Gehrels (1986)); which is slightly higher than the value for field stars. Adding giant planets with long periods, the rate becomes $3.4^{+3.3}_{-1.7}\%$, but this fraction is a lower limit that will increase with the follow-up of some other candidates (see Pasquini et al. 2012), which reveal suggestive signals for additional planetary companions. If these were confirmed, the frequency of giant planets would rise to $13^{+5.0}_{-2.5}\%$, in agreement with the rate of giant planets found by Mayor et al. (2011) for field stars.

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References

Baranne, A., Queloz, D., Mayor, M., et al. 1996, A&AS, 119, 373
Bonnell, I. A., Smith, K. W., et al. 2001, MNRAS, 322, 859
Bouchy, F. & Sophie Team. 2006, in Tenth Anniversary of 51 Peg-b, ed. L. Arnold, F. Bouchy, & C. Moutou, 319–325
Bramich, D. M., Horne, K., Bond, I. A., et al. 2005, MNRAS, 359, 1096
Cappetta, M., Saglia, R. P., Birkby, J. L., et al. 2012, MNRAS, 427, 1877
Cumming, A., Butler, R. P., Marcy, G. W., et al. 2008, PASP, 120, 531
Debes, J. H. & Jackson, B. 2010, ApJ, 723, 1703
Eisner, J. A., Plambeck, R. L., Carpenter, J. M., et al. 2008, ApJ, 683, 304
Gehrels, N. 1986, ApJ, 303, 336
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371
Hartman, J. D., Gaudi, B. S., Holman, M. J., et al. 2009, ApJ, 695, 336
Horne, J. H. & Baliunas, S. L. 1986, ApJ, 302, 757
Lee, Y. S., Beers, T. C., Sivarani, T., et al. 2008, AJ, 136, 2050
Lovis, C. & Mayor, M. 2007, A&A, 472, 657
Mathieu, R. D., Latham, D. W., Griffin, R. F., & Gunn, J. E. 1986, AJ, 92, 1100
Mayor, M., Marmier, M., Lovis, C., et al. 2011, ArXiv e-prints
Mayor, M., Pepe, F., Queloz, D., et al. 2003, The Messenger, 114, 20
Meibom, S., Torres, G., Fressin, F., et al. 2013, Nature, 499, 55
Mermilliod, J.-C. & Mayor, M. 2007, A&A, 470, 919
Mochejska, B. J., Stanek, K. Z., Sasselov, D. D., et al. 2006, AJ, 131, 1090
Mochejska, B. J., Stanek, K. Z., Sasselov, D. D., et al. 2005, AJ, 129, 2856
Montgomery, K. A., Marschall, L. A., & Janes, K. A. 1993, AJ, 106, 181
Önehag, A., Korn, A., Gustafsson, B., et al. 2011, A&A, 528, A85
Pace, G. & Pasquini, L. 2004, A&A, 426, 1021
Pasquini, L., Biazzo, K., Bonifacio, P., et al. 2008, A&A, 489, 677
Pasquini, L., Brucalassi, A., Ruiz, M. T., et al. 2012, A&A, 545, A139
Pasquini, L. & Pallavicini, R. 1991, A&A, 251, 199
Paulson, D. B., Saar, S. H., Cochran, W. D., & Henry, G. W. 2004, AJ, 127, 1644
Pepe, F., Mayor, M., Galland, F., et al. 2002, A&A, 388, 632
Pepper, J., Stanek, K. Z., Pogge, R. W., et al. 2008, AJ, 135, 907
Perruchot, S., Bouchy, F., et al. 2011, in SPIE Conf. Series, Vol. 8151
Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2004, ApJ, 612, 168
Pont, F., Husnoo, N., Mazeh, T., & Fabrycky, D. 2011, MNRAS, 414, 1278
Queloz, D., Henry, G. W., Sivan, J. P., et al. 2001, A&A, 379, 279
Quinn, S. N., White, R. J., Latham, D. W., et al. 2012, ApJ, 756, L33
Quinn, S. N., White, R. J., Latham, D. W., et al. 2013, ArXiv e-prints
Randich, S., Bragaglia, A., Pastori, L., et al. 2005, The Messenger, 121, 18
Randich, S., Sestito, P., Primas, F., et al. 2006, A&A, 450, 557
Sanders, W. L. 1977, A&AS, 27, 89
Santerne, A., Díaz, R. F., Moutou, C., et al. 2012, A&A, 545, A76
Sato, B., Izumiura, H., Toyota, E., et al. 2007, ApJ, 661, 527
Scargle, J. D. 1982, ApJ, 263, 835
Smolinski, J. P., Lee, Y. S., Beers, T. C., et al. 2011, AJ, 141, 89
Spurzem, R., Giersz, M., Heggie, D. C., & Lin, D. N. C. 2009, ApJ, 697, 458
Taylor, B. J. 2007, AJ, 133, 370
Tull, R. G. 1998, in SPIE Conf. Series, ed. S. D'Odorico, Vol. 3355, 387–398
van den Berg, M., Tagliaferri, G., et al. 2004, A&A, 418, 509
van Saders, J. L. & Gaudi, B. S. 2011, ApJ, 729, 63
Wright, J. T. & Howard, A. W. 2009, ApJS, 182, 205
Wright, J. T., Marcy, G. W., Howard, A. W., et al. 2012, ApJ, 753, 160
Wu, Y., Luo, A.-L., Li, H.-N., et al. 2011, RAA, 11, 924
Yadav, R. K. S., Bedin, L. R., Piotto, G., et al. 2008, A&A, 484, 609

Appendix A: CMD and membership probabilities

In this section we summarize the results presented in Pasquini et al. (2012), focusing in particular on the three stars discussed in the letter.
YBP1194, YBP1514, and S364 belong to the M67 sample that includes a total of 88 stars. All targets have V mag. between 9 and 15, and a mass range between 0.9-1.4 $M_{\odot}$.

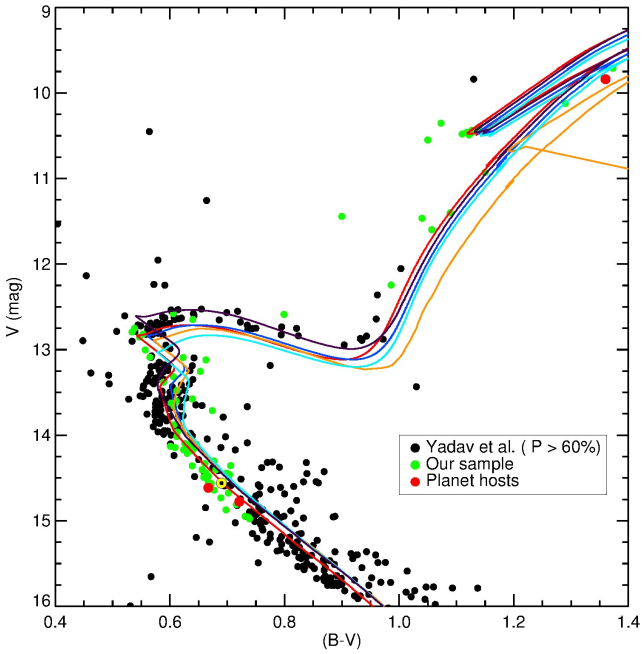

Fig. A.1. CMD of M67 (photometry from Yadav et al. 2008) for probable members (P_{μ} > 60%). The isochrones are taken from the BaSTI library (Pietrinferni et al. 2004). The isochrones in black, dark blue, and light blue correspond to 3.5 Gyr, 4.0 Gyr, and 4.5 Gyr with a reddening E(B-V)=0.041±0.004 (Taylor 2007). The isochrone in red is a 4.0 Gyr with a lower reddening (E(B-V)=0.02). The isochrone in orange is a 4.47 Gyr from Girardi et al. (2000) with E(B-V)=0.041±0.004. The location of the Sun, if it were within M67, is marked with a ⊙ in yellow.

We selected main-sequence stars (included YBP1194 and YBP1514) with a membership probability higher than 60% and a proper motion shorter than 6 mas/yr with respect to the average according to Yadav et al. (2008). For the giants we refer to Sanders (1977). The RV membership was established for the latter following the work of Mermilliod & Mayor (2007), who studied the membership and binarity of 123 red giants in six old open clusters, and of Mathieu et al. (1986), who made a very complete RV survey of the evolved stars of M67 with a precision of a few hundreds of $\mathrm{m\,s^{-1}}$. The majority of the other stars were selected according to Pasquini et al. (2008), who used several VLT-FLAMES exposures for each star to classify suspected binaries. We found that YBP1194, YBP1514, and S364 are probable RV members with a mean radial velocity within one-sigma from the average cluster RV. For the latter, we adopted the value of $\langle RV_{M67} \rangle = 33.724\,\mathrm{km\,s^{-1}}$and the dispersion of $\sigma = \pm 0.646\,\mathrm{km\,s^{-1}}$estimated in Pasquini et al. (2012).
Table 3 shows proper motions and membership probability for the three stars discussed. Details about selection criteria and motion errors can be found in the original Yadav et al. (2008) and Sanders (1977) works.
In Figure A.1, we report the observed region of the color-magnitude diagram (CMD), indicating in different colors the the

Table A.1. Object ID, proper motions, and membership probability of the targets; reference.

Object	$\mu_x \pm \Delta\mu_x$	$\mu_y \pm \Delta\mu_y$	Prob%	Reference
YBP1194	0.30±1.01	-0.42±0.65	99	Yadavet al. (2008)
YBP1514	-0.12±1.13	1.73±1.37	98	Yadavet al. (2008)
S364	-0.088	0.164	82	Sanders (1977)

position of the stars considered in this letter and the solar analog, as determined in Pasquini et al. (2008). The three stars analyzed in this work lie quite well on the cluster sequence in the CMD. We superimposed the isochrones from Pietrinferni et al. (2004) with solar metallicity and age corresponding to 3.5 Gyr (black curve), 4.0 Gyr (dark-blue curve) and 4.5 Gyr (light-blue curve). We also included the 4.0 Gyr isochrone (red curve) with a slightly lower reddening (E(B-V)=0.02 instead of 0.041 (Taylor 2007)). This curve seems to match the colors of the turnoff better (see also the discussion in Pasquini et al. 2012). In the same figure, we report the Padova isochrone using E(B-V)=0.041±0.004, with solar metallicity, age 4.47 Gyr, and Y=0.26 (Girardi et al. 2000).
Given that the values of stellar parameters have influence on the estimation of the planet masses, we evaluated the effects on the host star masses and radii of using isochrones with different ages and slightly lower reddening. While for the two main-sequence stars YBP1194 and YBP1514 we found no significant incidence, for the giant S364, an age uncertainty of ±0.5 Gyr and a lower reddening would induce an error on the star mass of 4% and on its radii of 3%. Therefore, we decided to include this effect in the uncertainties of S364 listed in Table 1 and in the error of the planet mass.

Table A.2. Relative RV measurements, RV uncertainties, bisector span, and ratio of the H_α core with respect to the continuum (see Pasquini & Pallavicini 1991) for YBP1194. All the RV data points are corrected to the zero point of HARPS.

BJD (-2450000)	RV ($km\,s^{-1}$)	σRV ($km\,s^{-1}$)	BIS span ($km\,s^{-1}$)	$H_\alpha$ratio	instrument
4489.51193	−0.000	0.009	−0.021029	0.038294	Sophie
4491.50617	−0.030	0.009	−0.042000	0.038689	Sophie
4842.84025	0.051	0.010	−0.018851	0.038897	Harps
4856.62544	0.013	0.012	−0.081895	0.038995	Harps
4862.59495	0.031	0.013	−0.009653	0.039465	Harps
5188.83049	0.002	0.010	−0.056037	0.039817	Harps
5189.82037	0.010	0.010	0.022874	0.039387	Harps
5190.79901	0.036	0.009	0.039774	0.038994	Harps
5214.85851	−0.030	0.013	0.008036	0.039872	Harps
5216.70466	−0.000	0.012	0.051777	0.037107	Harps
5594.79168	0.019	0.014	−0.021881	0.039218	Harps
5977.66236	0.037	0.010	−0.028000	0.037126	Harps
5986.51471	−0.034	0.009	−0.057833	0.038907	Sophie
6219.98852	0.049	0.027	−0.025204	0.037364	Het
6243.93406	−0.028	0.028	0.019138	0.036729	Het
6245.81040	−0.007	0.017	−0.026488	0.041533	Harps
6270.77262	0.009	0.019	−0.053592	0.039405	Harps
6286.00446	−0.066	0.025	−0.042748	0.036126	Het
6305.17913	0.017	0.014	−0.092977	0.038956	Harps
6316.76841	0.005	0.012	−0.021029	0.039405	Harps
6322.71086	−0.006	0.021	−0.028423	0.038896	Harps
6338.66079	0.034	0.026	−0.095893	0.037364	Het
6378.72343	0.002	0.026	0.024230	0.038289	Het

Table A.3. Relative RV measurements, RV uncertainties, bisector span, and ratio of the H_α core with respect to the continuum (see Pasquini & Pallavicini 1991) for YBP1514. All the RV data points are corrected to the zero point of HARPS.

BJD (-2450000)	RV ($km\,s^{-1}$)	σRV ($km\,s^{-1}$)	BIS span ($km\,s^{-1}$)	$H_\alpha$ratio	instrument
4858.72562	−0.037	0.017	−0.097357	0.040203	Harps
4861.71515	0.008	0.012	0.030042	0.039426	Harps
5214.87795	0.008	0.020	−0.056154	0.037161	Harps
5216.72426	−0.047	0.014	0.015647	0.042089	Harps
5260.70288	0.003	0.013	−0.042552	0.039905	Harps
5269.72337	0.059	0.014	0.035491	0.038077	Harps
5595.74177	−0.029	0.014	0.026610	0.039282	Harps
5626.15072	−0.039	0.014	−0.057171	0.039905	Harps
5943.29835	−0.037	0.013	0.015647	0.040103	Harps
5967.45833	0.008	0.023	−0.084845	0.039356	Harps
5968.59423	−0.031	0.014	−0.020833	0.039036	Harps
5977.68405	0.007	0.012	−0.051313	0.039475	Harps
5986.56139	0.068	0.010	−0.020833	0.039306	Sophie
6036.66109	−0.005	0.025	−0.054711	0.040201	Het
6245.83389	−0.037	0.015	0.025824	0.040109	Harps
6254.90496	−0.036	0.026	−0.035278	0.040001	Het
6270.81399	−0.068	0.019	0.014902	0.039345	Harps
6305.22499	−0.022	0.016	−0.031263	0.037032	Harps
6307.81028	−0.036	0.016	−0.016596	0.039764	Harps
6317.74917	−0.049	0.014	−0.071034	0.038687	Harps
6322.68946	0.016	0.019	−0.084845	0.040020	Harps
6332.68338	−0.021	0.016	−0.012640	0.039854	Harps
6335.68811	0.001	0.025	0.056131	0.041020	Het
6339.68307	0.066	0.025	−0.056093	0.042437	Het
6364.59175	0.007	0.024	0.011085	0.040285	Het

Table A.4. Relative RV measurements, RV uncertainties, bisector span, and ratio of the H_α core with respect to the continuum (see Pasquini & Pallavicini 1991) for S364. All the RV data points are corrected to the zero point of HARPS.

BJD (-2450000)	RV ($km\,s^{-1}$)	σRV ($km\,s^{-1}$)	BIS span ($km\,s^{-1}$)	$H_\alpha$ratio	instrument
2647.77191	−0.030	0.010	0.035310	-	Coralie
2682.68790	−0.070	0.010	−0.004670	-	Coralie
2695.70992	−0.077	0.011	0.022800	-	Coralie
3004.82521	0.009	0.012	0.046980	-	Coralie
3020.78490	−0.004	0.021	0.042690	-	Coralie
3046.73656	−0.016	0.010	−0.021670	-	Coralie
3055.71453	−0.039	0.012	0.010630	-	Coralie
4855.58011	−0.037	0.002	0.042682	0.038161	Harps
4860.32500	−0.036	0.008	0.042690	0.038048	Sophie
5216.82809	−0.012	0.002	0.071695	0.038278	Harps
5594.58582	−0.032	0.003	0.071762	0.038105	Harps
5977.55818	−0.071	0.002	0.064832	0.037733	Harps
5985.30291	−0.059	0.007	0.022666	0.038426	Sophie
6236.94284	0.004	0.018	0.050689	0.040027	Het
6245.76368	0.034	0.003	0.059181	0.038501	Harps
6245.86577	0.041	0.002	0.052050	0.038271	Harps
6269.71823	0.046	0.003	0.061007	0.041626	Harps
6270.75931	0.063	0.003	0.059963	0.038616	Harps
6302.68302	−0.006	0.003	0.057069	0.038056	Harps
6305.24544	−0.018	0.002	0.036772	0.037843	Harps
6309.75038	−0.010	0.002	0.056751	0.039626	Harps
6309.75141	−0.042	0.018	0.042921	0.039879	Het
6324.67965	−0.056	0.004	0.045385	0.038311	Harps
6331.69998	−0.051	0.020	0.043008	0.039356	Het
6332.69784	−0.038	0.003	0.045065	0.038067	Harps
6345.65885	−0.072	0.020	0.041555	0.039587	Het
6376.73341	0.072	0.021	0.022076	0.039445	Het