THE ELODIE PLANET SEARCH: SYNTHETIC VIEW OF THE SURVEY AND ITS GLOBAL DETECTION THRESHOLD

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Abstract

In this paper, we give a synthetic view of the ELODIE Planet Search programme: a short description of our instrument and the surveyed sample as well as a brief review of our detections. Moreover, we have obtained, through numerical simulations, the global survey sensitivity: a detection probability map in the $m_2$ versus $P$ diagram. We use this map for correcting our total number of detections for observational biases. Finally we derive the fraction of our sample stars hosting at least one giant planet.

Key words: Planets: exoplanets – Techniques: radial velocities

1. The ELODIE survey: quick view

The search for extra-solar planets with the ELODIE echelle spectrograph (Baranne et al. 1996) mounted on the 193-cm telescope at Observatoire de Haute-Provence (OHP) started in 1994. The initial sample contained 142 stars, out of which 51 Peg (HD 217014), the star hosting the first detected extra-solar planet (Mayor & Queloz 1995). The sample was largely modified in 1997. The to-date survey sample size amounts to 330 stars. 18 extra-solar planet candidates have been detected with ELODIE. 15 of these candidates are orbiting a star in our sample. The three other detections (Gl 876 b, HD 80606 b and HD 178911 Bb) result from other programmes. Here are the main characteristics of our survey:

- **ELODIE:** $\Delta V = 42,000$ echelle spectrograph mounted on the 193-cm telescope at OHP (CNRS, France). A detailed description of the instrument can be found in Baranne et al. 1996.

- **Instrumental precision:** $\approx 6.5$ m s$^{-1}$ (see Perrier et al. 2003 using the simultaneous Thorium-Argon technique.

- **Sample:** 330 solar-type stars brighter than $m_V = 7.65$ in the northern hemisphere. The fast rotators ($v \sin i > 4$ km s$^{-1}$) and the binaries were removed according to CORAVEL (Baranne et al. 1979) radial-velocity data (see Perrier et al. 2003 for details).

- **Detections:** 18 planets detected (15 within the above described planet-search sample). Some of these planets are in multiple systems: HD 37124 c (Udry et al. 2002),

Table 1. The 18 objects with minimum masses below 18 $M_{\text{Jup}}$ detected with ELODIE and planet candidates confirmed with this instrument

| Planet      | Reference                        |
|-------------|----------------------------------|
| 51 Peg b    | Mayor & Queloz 1995              |
| 14 Her b    | Naef et al. 2004                 |
| Gl 876 b    | Delbosse et al. 1998             |
| HD 209458 b | Mazeh et al. 2000                |
| HD 190228 b | Perrier et al. 2003              |
| HD 8574 b   | Perrier et al. 2003              |
| HD 50554 b  | Perrier et al. 2003              |
| HD 74156 b  | Naef et al. 2003                 |
| HD 74156 c  | Naef et al. 2003                 |
| HD 80606 b  | Naef et al. 2001                 |
| HD 106252 b | Perrier et al. 2003              |
| HD 178911 Bb| Zucker et al. 2002               |
| HD 20367 b  | Udry et al. 2002                 |
| HD 23596 b  | Perrier et al. 2003              |
| HD 33636 b  | Perrier et al. 2003              |
| HD 37124 c  | Udry et al. 2002                 |
| HD 150706 b | Udry et al. 2002                 |
| Gl 777 Ab   | Naef et al. 2003                 |

| Confirmed                       |
|--------------------------------|
| Ups And b                      | Naef et al. 2004 |
| Ups And c                      | Naef et al. 2004 |
| Ups And d                      | Naef et al. 2004 |
| 55 Cnc b                       | Naef et al. 2004 |
| 55 Cnc d                       | Naef et al. 2004 |
| 47 UMa b                       | Naef et al. 2004 |
| 70 Vir b                       | Naef et al. 2004 |
| HD 187123 b                    | Naef et al. 2004 |

As an example of detection, Fig. 1 shows the ELODIE updated orbital solution for 51 Peg published in Naef et al. 2004.

- **Confirmations:** Using ELODIE, we have confirmed the orbital solution for planet candidates around Ups And (HD 9826, Butler et al. 1997, Butler et al. 1999), 55 Cnc (HD 75732, Butler et al. 1997, Marcy et al. 2002), 47 UMa b (HD 95128, Butler & Marcy 1996), 70 Vir (HD
2. GLOBAL ELODIE SURVEY SENSITIVITY

We have determined, via numerical simulations, the global ELODIE survey sensitivity, i.e. the probability of detection in the secondary mass versus orbital period diagram. We give some details about these simulations in Sect. 2.1. In Sect. 2.2, we describe how we accounted for non-photonic error sources. We study the impact of various stellar properties on the sensitivity in Sect. 2.3. Finally, we present our results in Sect. 2.4.

2.1. Numerical simulations

We have computed, through numerical simulations, the detection probabilities for a grid in the $m_2$ versus $P$ diagram. The secondary mass and orbital period considered intervals are: $0.025 \leq m_2 \leq 20 \, M_{\text{Jup}}$ and $0.8 \leq P \leq 6000 \, \text{d}$. The total number of grid points is 3534. We have generated 5000 random orbits for each grid point using the following distributions:

- uniform distribution for $T_0$ (instant of periastron passage) and $\omega$ (longitude of the periastron)
- $e$ (orbital eccentricity): we have used the eccentricity distribution observed for the known extra-solar planet candidates
- $i$ (inclination of the orbital plane): the probability density we have used for $i$ is proportional to $\sin i \, di$

These confirmed planetary companions are also listed in table 1.

2.2. Non-photonic error sources

In order to account for the presence of non-photonic velocity error sources, we have determined the distribution of the observed velocity dispersion corrected for the photon noise for a subsample of target stars. This subsample contains the non-variable stars and the micro-variable stars for which the variability origin is unknown. The stars with planetary companions, the spectroscopic binaries (SB1 or SB2), the stars with close visual companions and the stars with blended spectra have been removed.

Figure 2 shows the distributions of the velocity dispersion for the remaining targets (240 stars). Their velocity dispersions have been quadratically corrected for their mean photon noise for building the displayed distributions. The remaining velocity dispersion sources present in these distributions are: the instrumental error, the stellar jitter, the stellar oscillations, the non-detected (or not yet characterized) light planets and the non-detected blended spectra. Non-photonic error contributions have been randomly generated in our simulations using these two distributions.

2.3. Impact of colour, metallicity and rotation

Figure 3 shows the impact of the $B-V$ colour index, the metallicity $[\text{Fe/H}]$ and the projected rotational velocity $v \sin i$ on the 90% detection limit obtained using the measurement dates and signal-to-noise ratios obtained for one of our sample stars. The photon noise errors have been
Figure 3. Impact of stellar properties on the 90% detection limit of one sample star: $B - V$ (top), $[\text{Fe/H}]$ (middle) and $v \sin i$ (bottom). An almost negligible impact of rotation and a weak impact of metallicity are observed. The moderate impact of colour is mostly due to the differences in primary mass.

computed using cross-correlation function parameters corresponding to the simulated stellar characteristics.

The impact of rotation is negligible up to $v \sin i = 4 \text{ km s}^{-1}$, the value we have used for selecting our sample of slow rotators. The impact of metallicity is very weak whereas the impact of colour is higher but mostly due to primary mass differences. The absence of metallicity impact on the detection limits further demonstrates that the observed difference between the metallicity distributions for stars with and without planets ([Santos et al. 2001] [Santos et al. 2003] [Santos et al. 2004]) does not result from an observational bias.

2.4. Results

Figure 4 shows the 50 and 90% typical detection limits for the ELODIE survey. The dotted curve is the 90% detection limit obtained without including non-photonic error sources except the 6.5 m s$^{-1}$ instrumental error. This illustrates the dramatic impact of these error sources (in particular the radial-velocity jitter induced by stellar activity). Planets detected around our sample stars are noted by filled dots. The open triangles represent planets detected with ELODIE around stars outside our sample or detections confirmed with ELODIE. The position of Jupiter is indicated with its symbol.

Probabilities of detection versus orbital period for different secondary masses (1 $M_{\text{Sat}}$, 1 $M_{\text{Jup}}$ and 10 $M_{\text{Jup}}$) are displayed in Fig. 5. The presence of non-photonic error sources is taken into account. 90% of the Jupiter-mass planets are detected up to $P \simeq 20 \text{ d}$ and 50% up to $P = 300 \text{ d}$. The probability of detection for brown-dwarf companions is above 90% for all the period interval. The daily and yearly features are also clearly visible here. The dotted curves are obtained without including the contribution of non-photonic error sources except for the 6.5 m s$^{-1}$ instrumental error. These curves clearly show the dramatic impact of stellar jitter (and other error sources) on the detection sensitivity.

We find no sensitivity decrease between 1 and 2 days. Thus, planets in this period range, the so-called "very hot Jupiters" (see e.g. [Konacki et al. 2003] [Bouchy et al. 2004])
Figure 5. ELODIE detection probability versus orbital period for various companion masses (solid curves). The dotted curves represent the detection probabilities obtained without accounting for non-photonic error sources.

[Konacki et al. 2004], would be easily detected if present around our sample stars.

3. Fraction of stars hosting a giant planet

Following our obtained ELODIE detection limits, we can correct our effective detections for all the observational biases. We can also derive, by inverting the detection probability map, the fraction $f$ of stars in our sample hosting at least one giant planet (the outer planets of the two systems are not considered here) with $m_2 \geq 0.47 \, M_{\text{Jup}}$ and for different period intervals. We find:

\[
\begin{align*}
  f &= 0.7 \pm 0.5\% \quad \text{for} \quad P < 5 \, \text{d} \\
  f &= 4.0 \pm 1.1\% \quad \text{for} \quad P < 1500 \, \text{d} \\
  f &= 7.3 \pm 1.5\% \quad \text{for} \quad P < 3900 \, \text{d}
\end{align*}
\]

Details about our numerical simulations and these results on the global ELODIE survey sensitivity will be published in a forthcoming paper (Naef et al. 2004 in prep.).

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