COULD GENIE DETECT HOT JUPITERS?

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ABSTRACT

The prime objective of GENIE (**G**round-based **E**uropean **N**ulling **I**nterferometry **E**xperiment) is to obtain experience with the design, construction and operation of an IR nulling interferometer, as a preparation for the DARWIN / TPF mission [1]. In this context, the detection of a planet orbiting another star would provide an excellent demonstration of nulling interferometry. Doing this through the atmosphere, however, is a formidable task. In this paper we assess the prospects of detecting, with nulling interferometry on ESO's VLT, a Hot Jupiter, a giant planet in a close orbit around its parent star. First we discuss the definition of the optimal target. Then we present a simulated observation of the Tau Bootis system, which suggests that GENIE, in a L′-band single Bracewell configuration, could detect the hot Jupiter in a few hours time with a signal-to-noise ratio of up to ~80. Although there are strong requirements on the control-loop performance, background subtraction and accuracy of the photometry calibration, we conclude that at present there do not seem to be fundamental problems that would prevent GENIE from detecting hot Jupiters. Hence the answer to the question in the title is **yes.**

1. INTRODUCTION

GENIE is a collaboration between ESO and ESA, and intended for commissioning on the VLTI in 2007. It is presently in its definition phase. In order to assess its performance, to assist in the requirements definition and to prepare science studies, we have developed a GENIE science simulator , GENIEsim [2]. Its inputs consists of specifications for the interferometer configuration, target source, observational scenario, atmospheric conditions, detector and control loop performance. The outputs are a series of detected photon-electron numbers (for constructive and destructive interference modes) as a function of time and wavelength, mimicking actual CCD output. The challenge we are facing is to extract from this output convincing evidence for the presence of a planet.

Even for a single Bracewell configuration, the VLTI allows quite some combinations between baseline and IR wavelength band. The 93 planetary systems identified so far with radial velocity or occultation methods, show star-planet separations ranging from 0.02 to several AU [6]. It is therefore a priori not obvious which combination between baseline, wavelength band and target will provide the best detection opportunity and a careful selection of the target is part of the preparation of the simulation.

2. TARGET SELECTION

The strategy we apply here is to first define the best possible target in terms of distance, spectral type, and orbital period, and then to see if there is a candidate on the list of stars with planetary systems that fits the description. The optimal target for a nulling interferometry experiment is close by, has a bright planet around a relatively dim star, with a contrast that is maximum for the chosen wavelength band, and with a separation that is matched to the interferometric pattern. There is some internal conflict in these requirements: a bright planet requires either a hot, bright star, which diminishes the contrast, or an as small as possible separation, which may put the planet inside the nulled part of the interferometric pattern. Moreover, massive, hot, bright stars are generally at greater distances than light, cool, dim stars. Also, while nulling interferometry at longer wavelengths relieves the requirements on the stability of the null, the atmospheric background noise is more severe. For an optimal target, these conflicting requirements are traded off against each other. Table 1 shows the results of such an exercise. As the figure of merit, we have chosen the signal-to-noise ratio for the detection of a planet, which is defined as:

$$\frac{S}{N} = \frac{S_p}{\sqrt{S_p + \sigma_{bg}^2 + \sigma_{leak}^2 + \sigma_{RON}^2}} \propto \sqrt{t} \qquad (1)$$

where S_p is the planetary signal, σ^2_{bg} is the variance of the background due to atmosphere and instruments,

σ^2_{leak} is the variance of the star light that is transmitted (leaked) by the nuller, and σ_{RON} is the rms read-out noise of the CCD detector. The variances σ^2_{bg} and σ^2_{leak} actually consist of the sum of two terms, one representing the pure Poissonian noise and equaling the average signal level, while the other is associated with the fluctuations of the detected intensity due to, in this case, fluctuating atmospheric and instrumental conditions [3].

The S/N ratio was evaluated for a single Bracewell configuration consisting of two UT telescopes, and varying the wavelength band, the baseline, the stellar temperature, the distance and the orbital period of the planet. In order to streamline this search through a five-dimensional parameter space, some simplifying assumptions were necessary. Instead of using the full GENIEsim code, we used analytical approximations to obtain values for the stellar leakage and associated noise [4]. The non-Poissonian fluctuations of the background noise are neglected in this particular approach (see below). Additional assumptions are: the planet is assumed to be in thermal equilibrium with the star; the size of the planet is equal to Jupiter (cf. [5]); the minimum orbital period is 3 days; and the minimum distance at which main-sequence M, K, G, F and A stars can be found are respectively 4, 10, 12, 14 and 25 pc (based on the statistics of stars accessible from Paranal).

From Table 1 it becomes clear that the best S/N ratio is to be expected for an L' band observation with a fairly long baseline of 89.4 m. This table also shows several trends, related to the trade-offs discussed before. The rms leakage, σ_{leak}, is (approximately) proportional to $\alpha=\pi\theta_*B/\lambda$, where θ_* is the angular size of the stellar disk and B the baseline projected onto the sky. As a consequence, σ_{leak} decreases with increasing λ, which explains the difference in obtainable S/N ratio between K and L′ band. Inside the K-band the loss of signal is traded against decrease in leakage when the star is further away. For the longer baselines the S/N ratio will not improve for A stars, because the increase in planetary flux (due to higher temperatures) does not compensate the extra leakage due to a larger stellar disk. In the M and N′ band advantage of lower leakage is undone by the increased noise from the background, which completely dominates the N′ band results.

Table 1. Estimated best signal-to-noise ratio for the detection of hot Jupiters (bold face), as a function of baseline and wavelength band, obtainable in 10^4 s. Next line, null depth, defined as the total stellar flux divided by the flux transmitted through the nulling interferometer, and modulation is defined as the ratio of maximum and minimum transmission. Then, stellar temperature in K, and spectral type. Finally, distance in pc and orbital period of the hot Jupiter, in days. All planets are one Jupiter radius in size, cf. [5].

S/N ratio in 10^4 sec null depth / modulation T_{star} / spectral type distance [pc] / period [d]			Baseline					
			UT 1–4 130.2 m	UT 1–3 102.4 m	UT 2–4 89.4 m	UT 3–4 62.5 m	UT 1–2 56.6 m	UT 2–3 46.6 m
Band	λ_{cen} [μm]	$\Delta\lambda$ [μm]						
K	2.2	0.4	**20.1** 283 / 239 7400 / F0 37.5 / 3.0	**20.1** 283 / 239 7400 / F0 29.5 / 3.0	**20.1** 288 / 241 7400 / F0 26.0 / 3.0	**20.1** 283 / 240 7400 / F0 18.0 / 3.0	**20.1** 289 / 242 7400 / F0 16.5 / 3.0	**20.0** 321 / 250 7400 / F0 14.5 / 3.0
L′	3.8	0.6	**82.0** 284 / 277 5700 / G3 15.0 / 3.0	**87.8** 329 / 308 5600 / G4 12.5 / 3.0	**88.1** 402 / 339 5700 / G3 10.5 / 3	**76.4** 662 / 396 6000 / G0 12.5 / 3.3	**71.8** 778 / 432 6000 / G0 12.5 / 3.5	**62.5** 1047 / 528 6000 / G0 12.5 / 4.3
M	4.8	0.6	**67.1** 227 / 219 7400 / F0 14.5 / 3.0	**60.1** 354 / 295 7400 / F0 14.5 / 3.3	**54.3** 452 / 377 7400 / F0 14.5 / 4	**51.0** 477 / 454 3400 / M1 4.5 / 3	**47.9** 569 / 502 3400 / M1 4.5 / 3	**39.6** 791 / 566 3400 / M1 4.5 / 3
N′	11.25	2.5	**8.7** 612 / 532 3400 / M1 4.5 / 3.0	**6.7** 939 / 743 3400 / M1 4.5 / 3.8	**5.7** 1187 / 923 3400 / M1 4.5 / 3.8	**3.7** 2124 / 1483 3400 / M1 4.5 / 6.8	**3.2** 2468 / 1657 3400 / M1 4.5 / 7.5	**2.5** 3243 / 2024 3400 / M1 4.5 / 9.3

Table 2. Properties of the currently most promising, spectroscopically confirmed, Hot Jupiter targets [5, 6].

	Star								Planet					
Name	Spectr type	Temp. [K]	dist. [pc]	Mass [$M_\odot$]	Rad. [$R_\odot$]	Lum. [$L_\odot$]	α	δ	M sin*i* [M_J]	period [d]	e	a [AU]	T_{eff} [K]	Radius [R_J]
Tau Boo b	F7V	6276	17	1.42	1.22	3.2	13:47:15.7	+17:27:25	4.14	3.313	0.016	0.045	1600	1
HD179949 b	F8V	6194	27	1.24	1.18	2.18	19:15:33.2	–24:10:46	0.93	3.092	0.00	0.047	1540	1
Gliese 86 b	K1V	5070	13	0.79	0.82	0.50	02:10:25.9	–50:49:25	4.9	15.8	0.04	0.117	660	1

The jump from M1 dwarf to F0 star in the M band is again a result of the trade-off between stellar radius and planetary flux, which are both larger for hotter stars. The general trend for the nulling depth and modulation ratio to improve with decreasing baseline, is due to the fact that both these ratios have a denominator proportional to the leakage signal, which is itself (approximately) proportional to α^2. Table 1 clearly demonstrates that there is no relation between the nulling depth or modulation ratio and the actual S/N ratio for planetary detection.

We have attempted to find a matching target from the list of stars with confirmed planets [6], and found that Tau Bootis matches best the properties for the highest S/N detection in Table 1, and is accessible from Paranal in Chile. Its properties are summarized in Table 2, together with two other likely candidates. A detailed simulation of its detection with GENIEsim is discussed in the next section.

3. PERFORMANCE OF A SINGLE-BRACEWELL CONFIGURATION

Fig. 1a illustrates the output of a simulation of a one-hour Tau Boo b observation with GENIEsim for a single Bracewell formed by UT's 2 and 4. For five different wavelengths in the L′-band range the total detected output signal in detected electrons is shown. Note that the signal is boxcar averaged over a 60 sec. bin. The decline of the signal is due to the motion of the source across the sky. In Fig. 1b the S/N ratio for the different wavelengths is shown as a function of time. After one hour integration, the S/N ratios lie in the range from 51 to 77, which is in good agreement with the preliminary estimates in Table 1. Fig. 1c compares the different noise sources to the planetary signal, showing that the noise due to stellar leakage and IR background are comparable, and dominate the S/N ratio.

One of the main tasks of GENIE is to correct for optical path differences (OPD) between the two arms of the interferometer, which enhance the stellar leakage. In GENIEsim we currently distinguish four main sources: *a.* static, due to a small phase error in the achromatic phase shifter, (~7 mrad [9]); *b*. wavelength-independent OPD fluctuations, due to the atmospheric piston effect, with a rms value of about 24 nm / 40 mrad (after correction by the VLTI and additional GENIE OPD control loops); *c.* wavelength-dependent OPD fluctuations, due to water-vapour dispersion [7, 8], with a rms value of 21 nm / 34 mrad after the GENIE control loop; *d.* intensity fluctuations between the two arms, due to Strehl ratio and scintillation fluctuations, with a rms value of 0.014 after the VLTI MACAO and GENIE control loops. Although the precise values of these errors remain debatable, it is clear that technical solutions do exist and can be implemented for these effects.

More fundamental is the problem of the IR background fluctuations. While the instrumental background stems from a thermally stabilized environment, the atmospheric background is uncontrollable. The average background can be instantaneously subtracted from the signal, e.g. by placing two additional fibers on either side of the science fiber in the focal plane. Assuming that the background is highly correlated over a few arcsec., this method can even deal with a fluctuating background. This is done in the current runs of GENIEsim. However, the photon noise from the background cannot be calibrated away and will reduce the S/N ratio (see Fig. 1c).

Comparing the signal with and without the planetary contribution shows that in order to actually disentangle the planetary signal from the other contributions, accurate photometry is required. Moreover, the photometry has to be stable over hours to days, as the modulation of the planetary signal takes place on these timescales. Fig. 1a shows that in order to detect the planet, this calibration should have a (relative) accuracy better than 1%. We have several options to accomplish this.

- Calibration of the signal with an (unresolved) star of same spectral type is a first step. This will reduce the problem from absolute to relative calibration.
- Next the comparison of the constructive and destructive spectrally resolved signals will tell us whether the nulled signal contains spectral features indicative of the presence of a planet.
- Thirdly, modulation of the OPD might indicate whether the stellar leakage is due to bad nulling or the presence of a planet.
- And finally, if everything else fails, we could consider calibrating the stellar leakage with a double Bracewell configuration. This would imply a major complication, because in order to combine the signals from four telescopes, not one, but actually three GENIEs are required.

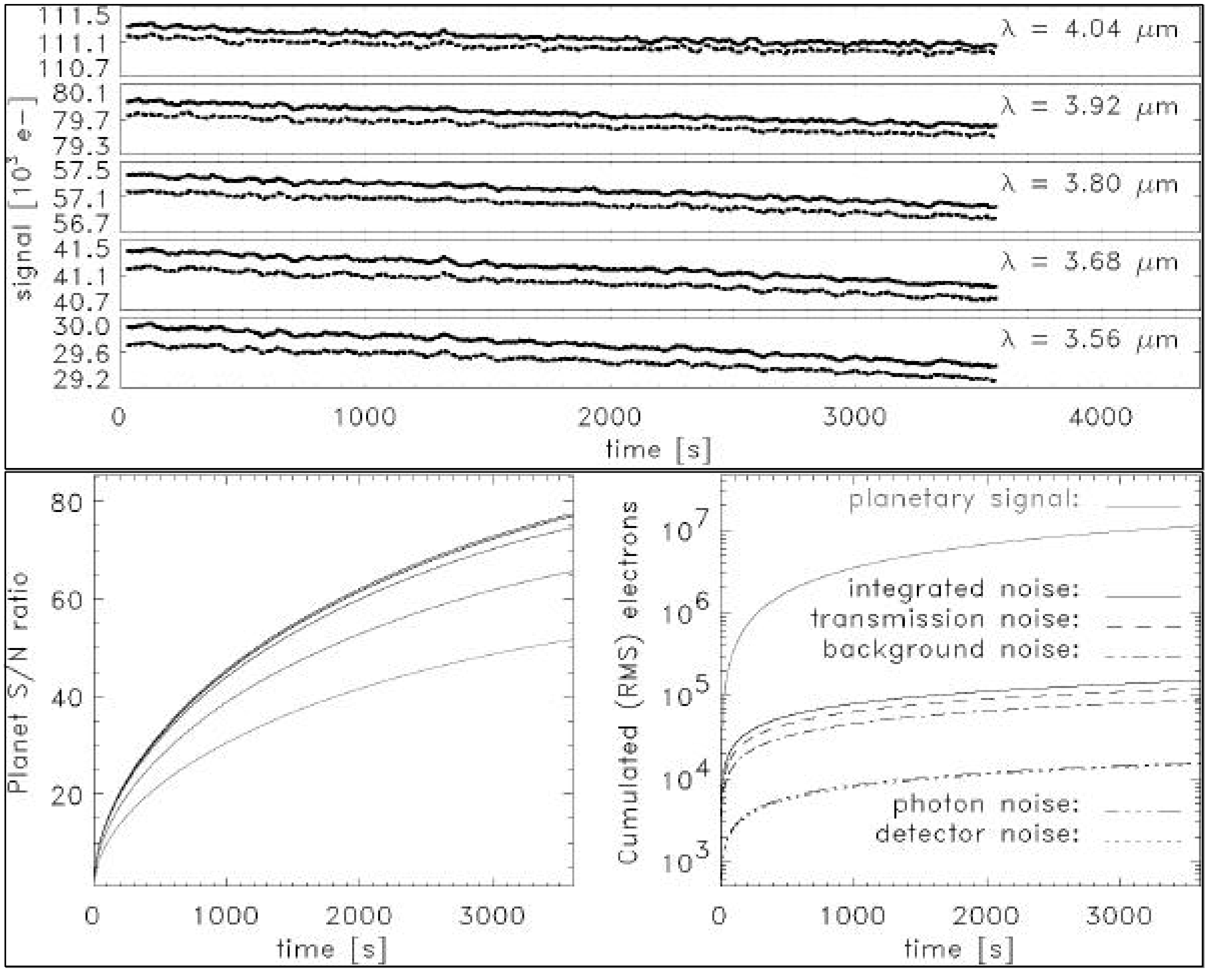

Fig. 1 ***a.*** Simulated total detected signals, for different wavelengths, with (solid) and without (dotted) the planetary light. Time series were boxcar averaged over 60 sec. ***b.*** Expected signal-to-noise ratio's for the planetary detection, for different wavelengths (dark: 4.04 mm, light: 3.56 mm). ***c.*** Various noise sources compared to the planetary signal. Note that background noise includes the background photon noise.

4. CONCLUSIONS

In this paper we discuss the simulated observation of Tau Bootis, a nearby star for which the presence of a massive planet in close orbit has been inferred spectroscopically. These simulations suggest that GENIE, in a L'-band single Bracewell configuration, could detect the hot Jupiter in a few hours time with a signal-to-noise ratio of about 80. There are, however, several provisions. The first is that the proposed control loop performances and background subtraction are feasible in reality. The second is that the nulled signal photometry can be calibrated to within a per cent accuracy, in order to infer the presence of the planet from the light-curve modulation. In a second stage, spectral features can be used to perform planetary spectroscopy. At present there do not seem to be fundamental problems that would prevent GENIE from detecting hot Jupiters.

5. REFERENCES

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