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Additional Keplerian Signals in the HARPS data for Gliese 667C: Further Analysis

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Abstract. A re-analysis of Gliese 667C HARPS precision radial velocity data was carried out with a Bayesian multi-planet Kepler periodogram (from 0 to 7 planets) based on a fusion Markov chain Monte Carlo algorithm. The most probable number of signals detected is six with a Bayesian false alarm probability of 0.012. The residuals were shown to be consistent with white noise. The six signals detected include two previously reported with periods of 7.198 (b) and 28.14 (c) days, plus additional periods of 30.82, 38.82, 53.22, and 91.3 days. The existence of these Keplerian-like signals suggest the possibility of additional planets in the habitable zone of Gl 667C although some of the signals could be artifacts arising from the sampling or stellar surface activity. N-body orbital integrations are being undertaken to determine which of these signals are consistent with a stable planetary system. Preliminary results demonstrate that four of the signals, with periods of 7.2, 28.1, 38.8, & 91 d, are consistent with a stable 4 planet system on time scales of 10^7 yr. The $M \sin i$ values are ~ 5.5, 4.4, 1.9, and 4.7 $M_\oplus$, respectively.

Keywords. stars: planetary systems; methods: statistical; methods: data analysis; techniques: radial velocities

1. Introduction

This paper reports progress in the interpretation of additional Keplerian signals that were detected in a Bayesian re-analysis (Gregory 2012a) of the HARPS radial velocity data (Delfosse *et al.* 2013) for Gliese 667C. Gliese 667C (Gl 667C), is an isolated M dwarf component of a hierarchical triple system. The two others components, Gl 667AB, are a closer couple of K dwarfs (semi-major axis of 1.82 AU, period of 42.15 years and a total mass of 1.27 $M_\odot$). Gl 667C is the lightest component with a mass of 0.310 ± 0.019 $M_\odot$ (Anglada-Escudé *et al.* 2012). It is at an estimated distance of ~ 300 AU from Gl 667AB.

In 2011, Bonfils *et al.* (2011) reported a super-earth Gl 667Cb ($M \sin i = 5.9$ $M_\oplus$) with a period of 7.2 d and evidence for two other interesting periods of 90 and 28 d. The 28 d period was of particular interesting because it would fall in the HZ. Two recent papers (Anglada-Escudé *et al.* 2012 & Delfosse *et al.* 2013), have confirmed planet Gl 667Cb and a 28 d period planet Gl 667Cc ($M \sin i = 4.3$ $M_\oplus$) in the HZ.

The six Keplerian signals detected by Gregory (2012a), included the two previously reported with periods of 7.198 (b) and 28.14 (c) days, plus additional periods of 30.82, 38.82, 53.22, and 91.3 days. The Bayesian false alarm probability for a six signal model was found to be 0.012. The existence of these Keplerian-like signals suggest the possibility of additional planets in the habitable zone of Gl 667C, although some of the signals could be artifacts arising from the sampling or stellar surface activity. Delfosse *et al.* (2013) concluded that the rotation period of the star is ~ 105 d, based on a periodogram of the stellar activity diagnostic (FWHM of the CCF). We initially suspected the 53 d signal was the second harmonic of the star's rotation period. However, our own analysis of the diagnostic data indicates that the dominant spectral feature in the Lomb-Scargle periodogram of the FWHM shifts from a period of 105 d based for the first 107 FWHM points to 100 d based on the last 107 points. We now entertain the possibility that 53 d feature may not be an artifact.

2. New Results

We are employing the following two-step process to test whether a subset of the six signals are consistent with a dynamically stable planetary system. In the first step the likelihood function of the fusion MCMC (Gregory 2012b) was modified so the predicted reflex motion of the star consists of the sum of two parts. The first part is the reflex motion of the star due to the n planets, derived from a fourth order Hermite N-body integrator (Peit Hut and Jun Makino available on their 'Art of Scientific Computing website'). The second part consisted of m independent Kepler signals where $n + m = 6$. The calculation assumes that n of the signals are due to planets and the remaining m signals are artifacts which can be approximately modeled by Keplerians. To draw starting parameters for this modified fusion MCMC run, we first filtered the original fusion MCMC parameter sets obtained by Gregory (2012a) to find all parameter sets that were pair wise Lagrangian or Hill stable according to Barnes & Greenberg (2006), to pick out low eccentricity solutions. Thus the first step is attempting to find n planets plus m artifact signals that provide a good fit to the radial velocity data starting from the original fusion MCMC results.

The second step is to see if an n planet model from the first step is stable on a longer time scale of 10^7 yr using two different N-body integrators including HNBody due to Rauch & Hamilton (2002). Preliminary results demonstrate that four of the signals, with periods of 7.2, 28.1, 38.8, and 91 d, are consistent with a stable 4 planet system on time scales of 10^7 yr. The corresponding $M \sin i$ values are ~ 5.5, 4.4, 1.9, & 4.7 $M_\oplus$, respectively, and the semi-major axes are $\sim 0.049, 0.12, 0.15, \&\ 0.27$ AU. This places the 28.1 and 38.8 d planetary candidates in the central region of the habitable zone. Other combinations of n planetary candidates remain to be explored.

Note: Very recently, Anglada-Escudé *et al.* (2013) announced additional candidates with periods of 39, 62, 92, & 260 d and a hint of a seventh period of 17 d.

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