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Bayesian Model Selection and Extrasolar Planet Detection

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Abstract. The discovery of nearly 200 extrasolar planets during the last decade has revitalized scientific interest in the physics of planet formation and ushered in a new era for astronomy. Astronomers searching for the small signals induced by planets inevitably face significant statistical challenges. For example, radial velocity (RV) planet searches (that have discovered most of the known planets) are increasingly finding planets with small velocity amplitudes, with long orbital periods, or in multiple planet systems. Bayesian inference has the potential of improving the interpretation of existing observations, the planning of future observations and ultimately inferences concerning the overall population of planets. The main obstacle to applying Bayesian inference to extrasolar planet searches is the need to develop computationally efficient algorithms for calculating integrals over high-dimensional parameter spaces. In recent years, the refinement of Markov chain Monte Carlo (MCMC) algorithms has made it practical to accurately characterize orbital parameters and their uncertainties from RV observations of single-planet and weakly interacting multiple-planet systems.

Unfortunately, MCMC is not sufficient for Bayesian model selection, i.e., comparing the marginal posterior probability of models with different parameters, as is necessary to determine how strongly the observational data favor a model with $n + 1$ planets over a model with just n planets. Many of the obvious estimators for the marginal posterior probability suffer from poor convergence properties. We compare several estimators of the marginal likelihood and feature those that display desirable convergence properties based on the analysis of a sample data set for HD 88133b Fischer et al. (2005). We find that methods based on importance sampling are most efficient, provided that a good analytic approximation of the posterior probability distribution is available. We present a simple algorithm for using a sample from the posterior to construct a mixture distribution that approximates the posterior and can be used for importance sampling and Bayesian model selection. We conclude with some suggestions for the development and refinement of computationally efficient and robust estimators of marginal posterior probabilities.

1. Introduction

Recent collaboration between astronomers and statisticians has led to a better understanding of the particular challenges associated with Bayesian analysis of

dynamical planet detections. In this paper, we briefly review the state of the art of Bayesian parameter estimation, model selection, and experimental design in the context of extrasolar planet searches. Then, we discuss recent work on Bayesian model selection, demonstrating the properties of several estimators of the marginal posterior probability using an actual set of data from an RV planet search.

1.1. Observational Data

In RV surveys, the velocity of the central star is precisely monitored for periodic variations which could be caused by orbiting companions (see Fig. 1, left). Each individual observation can be reduced to an estimate of the observational uncertainty (σ_k) and a measurement of the star’s RV (v_k) relative to the j_k th velocity reference at time t_k . Because each RV measurement is based on calculating the centroid of thousands of spectra lines and averaged over hundreds of sections of the spectrum, the observational uncertainties of most current echelle based RV surveys can be accurately estimated and are nearly Gaussian (Butler et al. 1996). There may also be intrinsic stellar variability (“jitter”) that we model as an addition source of uncorrelated Gaussian noise with variance s^2 and add to the measurement uncertainties in quadrature. If the velocity observations (\vec{v}_θ) were generated by the model specified by \mathcal{M} and model parameters $\vec{\theta}$, then the probability of measuring the observed velocities is

$$L(\vec{\theta}) \equiv p(\vec{v}|\vec{\theta}, \mathcal{M}) = \prod_k \frac{1}{\sqrt{2\pi(\sigma_k^2 + s^2)}} \exp \left[-\frac{(v_\theta(t_k, j_k) - v_k)^2}{2(\sigma_k^2 + s^2)} \right], \quad (1)$$

assuming that the errors in individual observations and the “jitter” are both normally distributed and uncorrelated.

1.2. Theoretical Model

Specifying the mass and six phase space coordinates of each body in a planetary system at a specified time provides a complete description of the system. In practice, it is convenient to choose the osculating Keplerian orbital elements (orbital period, P , orbital eccentricity, e , inclination relative to the plane of the sky, i , argument of periastron measured from the plane of the sky, ω , longitude of ascending node, Ω , and mean anomaly, M) for each planet in Jacobi coordinates, since the mean anomaly is the only one of these orbital elements that changes with time for a planet on an unperturbed Keplerian orbit. The observed stellar velocity is the sum of the line of sight velocity of the center-of-mass and the projection of the reflex velocity due to any planetary companions onto the line of sight. For multiple planet systems, it can be important to use complete n-body simulations to model the planetary motions accurately (e.g., GJ876; Laughlin et al. 2005; Rivera et al. 2005). However, in most cases, the mutual planetary perturbations are negligible on time scales comparable to the duration of observations. In such cases, the RV perturbations due to a multiple planet system can be modeled as the linear superposition of multiple non-interacting Keplerian orbits, $v_\theta(t, j) = C_j + \sum_p \Delta v_p(t)$, where C_j is the j th velocity reference. While there is a single mean line of sight velocity of the center of motion, it is important

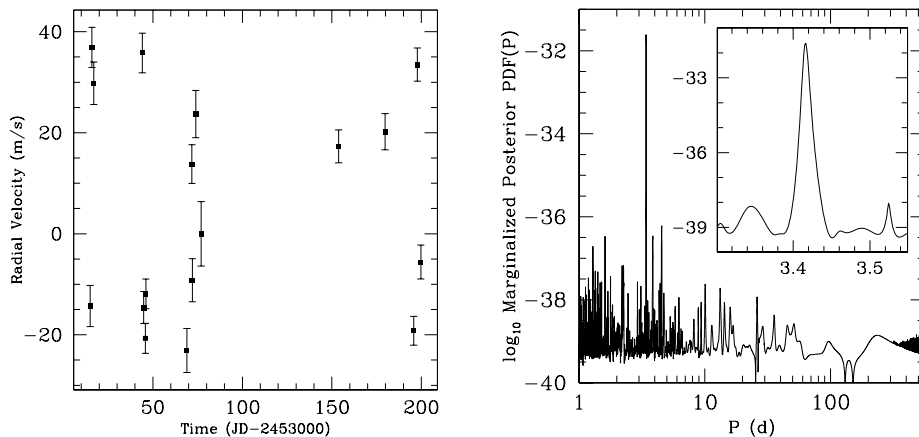


Figure 1. Left: The 17 RV observations of HD 88133 published in Fischer et al. (2005) plotted versus the time of observation. Right: The log posterior probability marginalized over all model parameters except the orbital period, assuming a single planet on a circular orbit (i.e., the Bayesian generalization of the periodogram) and the observational data shown on the left.

to use separate constants, C_j for each observatory/spectrograph pair, since the velocities are measured differentially relative to a reference velocity that is unique to each observatory. The perturbation to the stellar RV (Δv_p) due to a planet on a Keplerian orbit is given by $\Delta v_p(t) = K_p [\cos(\omega_p + T_p) + e_p \cos(\omega_p)]$ where p labels the planet, K is the velocity semi-amplitude and T is the true anomaly, which implicitly depends on time. The true anomaly (T) is related to the eccentric anomaly (E) via the relation $\tan(T/2) = (1+e)^{1/2}(1-e)^{-1/2} \tan^{1/2}(E/2)$. The eccentric anomaly is related to the mean anomaly (M) via Kepler's equation $E(t) - e \sin(E(t)) = M(t) - M_o = 2\pi t/P - M_o$ where M_o is a constant, the orbital phase at $t = 0$. Unfortunately, RV observations alone are not sensitive to the orbital inclination relative to the plane of the sky (i) or the longitude of ascending node (Ω). Therefore, RV observations by themselves can only measure the minimum mass ratio, $m_{\min}/M_* = m \sin i/M_*$, that is a function of K , P , e , and M_* , where M_* is the stellar mass, typically estimated by independent astronomical observations.

1.3. Bayesian Framework

To quantitatively analyze the available observational constraints, we employ the techniques of Bayesian inference. By treating both the observation and the model parameters as random variables, Bayesian inference is able to address statistical questions in a mathematically rigorous fashion. The joint probability, $p(\vec{v}, \vec{\theta}|\mathcal{M})$, can be expressed as the product of the likelihood ($L(\vec{\theta}) \equiv p(\vec{v}|\vec{\theta}, \mathcal{M})$), the probability of the observables given the model parameters), and a prior probability distribution function ($p(\vec{\theta}|\mathcal{M})$) which is based on previous knowledge of the model parameters. Note that each of the probability distribution functions (PDFs) is conditioned on the assumption of a model, \mathcal{M} , that includes the meaning of the model parameters, $\vec{\theta}$, and their relationship to the observational data,

\vec{v} . Bayes's theorem allows one to compute a posterior probability density function, $p(\vec{\theta}|\vec{v}, \mathcal{M})$, which incorporates the knowledge gained by the observations \vec{v} ,

$$p(\vec{\theta}|\vec{v}, \mathcal{M}) = \frac{p(\vec{\theta}|\mathcal{M})p(\vec{v}|\vec{\theta}, \mathcal{M})}{\int p(\vec{\theta}|\mathcal{M})p(\vec{v}|\vec{\theta}, \mathcal{M}) d\vec{\theta}}. \quad (2)$$

This paper is particularly interested in the case when there are multiple viable models (e.g., no planet model, one planet model, two planet model, etc.) for the current data set. In this case, the posterior for a given model and set of parameters is given by $p(\vec{\theta}, \mathcal{M}|\vec{v}) = p(\mathcal{M})p(\mathcal{M}|\vec{v})p(\vec{\theta}|\vec{v}, \mathcal{M})$, where $p(\mathcal{M})$ is the prior probability of model \mathcal{M} and the marginal posterior probability for model \mathcal{M} is given by

$$m(\vec{v}) \equiv p(\mathcal{M}|\vec{v}) = \int p(\vec{\theta}|\mathcal{M})p(\vec{v}|\vec{\theta}, \mathcal{M}) d\vec{\theta}. \quad (3)$$

We briefly review recent progress in sampling from $p(\vec{\theta}|\vec{v}, \mathcal{M})$ via MCMC in §1.5 and introduce and compare algorithms for evaluating of $m(\vec{v})$ in §2.

1.4. Choice of Priors

In Table 1, we list the priors used for each model parameter in this work. While the choice of these and other parameters can be fine-tuned for a given problem, we suggest these choices as a starting point for the Bayesian analysis of radial velocity data sets. Physical and geometric considerations lead to natural choices for the prior PDFs for most of the model parameters (see Table 1). A few of the priors merit closer attention. The cutoff at a minimum orbital period is chosen to be less than the smallest orbital period of known extrasolar planets, but this is somewhat larger than the theoretical limit (the Roche limit occurs at ~ 0.2 d for a $10M_{\text{Jup}}$ planet around a $1M_{\odot}$ star). The cutoff at a maximum orbital period is much longer than any known extrasolar planet, but is chosen to be roughly where perturbations from passing stars and the galactic tide would disrupt the planet's orbit. The cutoff at a maximum velocity semi-amplitude is chosen to be a function of orbital period, so that the cutoff corresponds to a constant planet-star mass ratio. In this paper, we set $K_{\text{max}} = 2129\text{m/s}$, which corresponds to a maximum planet-star mass ratio of 0.01. This choice is primarily based on the observed distribution of extrasolar planet masses. Clearly, there are stellar binaries with much larger velocity amplitudes, but this limit can be considered the definition of a planet. While the possibility of arbitrarily small masses (and hence velocity amplitudes) prevents a physical justification for a lower cutoff, K_{min} , it is not possible to detect or constrain the orbital parameters of a sufficiently low-mass planet. To keep the prior distribution normalizable, we impose breaks in the priors for K and s at K_0 and s_0 , chosen to be at a velocity amplitude less than the smallest detectable velocity amplitude. For a data set with N_{obs} RV measurements with typical measurement precision of $\bar{\sigma}$, we suggest setting $K_0 \leq \bar{\sigma}\sqrt{50/N_{\text{obs}}}$ (Cumming 1999). For the reference prior, we chose $s_0 = K_0 = 1\text{m/s}$, somewhat arbitrarily, but motivated by the current state of the art in RV planet searches (Asher Johnson et al. 2006). For systems where a planet is clearly detected, the shape of the posterior will not be sensitive to our assumptions about the prior for small values of K , but for planets which are marginally detected, this choice may become significant. If the posterior

distribution has significant probability near $K \simeq K_o$, then one should check how sensitive any conclusions are to the choice of K_o .

Table 1. SAMSI Exoplanet Working Group Reference Priors

Model Parameter	Variable	Prior Distribution	Minimum	Maximum
Amplitude of jitter	s	$\frac{(s+s_0)^{-1}}{\log\left(1+\frac{s_{\max}}{s_0}\right)}$	0 m/s	K_{\max}
Velocity offset	C_j	Parameters for each velocity reference $\frac{1}{C_{\max}-C_{\min}}$	$-K_{\max}$	K_{\max}
Orbital period	P_i	Parameters for each planet $\frac{P_i^{-1}}{\log(P_{\max}/P_{\min})}$	1 d	10^3 yr
Velocity semi-amplitude	K_i	$\frac{(K_i+K_0)^{-1}}{\log\left[1+\frac{K_{\max}}{K_0}\left(\frac{P_{\min}}{P_i}\right)^{1/3}\right]}$	0 m/s	$K_{\max}\left(\frac{P_{\min}}{P_i}\right)^{\frac{1}{3}}$
Orbital eccentricity	e_i	$\frac{1}{2\pi}$	0	1
Argument of periastron	ω_i	$\frac{1}{2\pi}$	0	2π
Orbital phase	M_i	$\frac{1}{2\pi}$	0	2π

1.5. Previous Research

Identifying the correct orbital solution from a set of RV (or other dynamical) observations is challenging due to the necessity of considering a very large parameter space of possible solutions (see Fig. 1, right). For RV planet searches, there are at least five model parameters per planet and one model parameter per observatory. To make the global search problem tractable, RV data sets are traditionally searched for sinusoidal signals (potential planets) using a periodogram. The advantage of the periodogram is that it is extremely tractable computationally ($O(n \log n)$) and can be quite useful for identifying potential orbital periods. Then Levenberg-Marquardt (LM) minimization (Press et al. 1992) is applied starting from several initial guesses of orbital solutions near each of the potential orbital periods identified by the periodogram. If the quality of the fit is consistent with the combination of the observational uncertainties (Butler et al. 1996) and the expected intrinsic stellar variability (Wright 2005), then estimates of the uncertainties in orbital parameters are obtained by repeatedly finding the best-fit orbital parameters (with LM) to several synthetic data sets generated via bootstrap resampling (with replacement) of the observational data (Press et al. 1992). These methods work quite well for analyzing stars with a single planet on a low-eccentricity, short-period (relative to the duration of the observations) orbit when the velocity perturbation is large (relative to the measurement uncertainties). Since such planets are the easiest to discover, they are common among the known sample of planets, and the traditional frequentist methods have proven quite valuable in their discovery.

In recent years, RV searches have become increasingly sensitive to planets with small velocity amplitudes and/or long orbital periods, as well as planets in multiple planet systems. Bayesian inference can help with each of these challenges and has the potential to significantly improve the sensitivity of detections and accuracy of orbital determinations. Recent work has begun to develop the framework and computational tools to make this happen. For example, Cumming (2004) discussed the relationship between the periodogram method and a Bayesian analysis that assumes any planet is on a circular orbit. Ford (2006b) combined brute force Monte Carlo (to integrate over orbital period) and the Laplace approximation (to integrate over the remaining model parameters) to render Bayesian model selection practical for planets assumed to be on a circular orbit (e.g., short-period planets prone to tidal circularization). MCMC has been applied to estimate orbital parameters and their uncertainty and to help understand the situations where traditional frequentist methods leave significant room for improvement (Ford 2005; Driscoll 2006). Gregory (2005a) and Ford (2006a) have automated the determination of parameters of the candidate transition PDFs. Ford (2006a) has also identified non-linear candidate transition PDFs that dramatically accelerate the convergence of MCMC. These advances make it computationally feasible for MCMC to characterize the allowed orbital solutions for single planets or weakly-interacting multiple planet systems (e.g. Ford, Lystad & Rasio 2005). Gregory (2005b) has applied parallel tempering to allow MCMC to explore multiple orbital solutions widely separated in parameter space. (Loredo 2004) developed the theoretical framework for applying Bayesian adaptive experimental design to dynamical extrasolar planet searches, and Ford (2006b) developed computationally practical algorithms for applying these techniques to adaptively schedule radial velocity observations. Bayesian techniques are just beginning to be applied to analyze the population of extrasolar planets (Ford & Rasio 2006; Loredo 2006).

2. Algorithms for Applying Bayesian Model Selection To Extrasolar Planets

While MCMC techniques have proven very efficient for sampling from the posterior distribution for orbital parameters of extrasolar planets (Ford 2006a, e.g.), MCMC does not directly determine the normalizing constant of the posterior distribution. While this is not necessary for parameter estimation (within a single model), it is essential when considering multiple possible models (e.g., no planet, one planet, two planets...). Clyde (2006) reviews the state of modern techniques for Bayesian model selection from a statistics perspective. In this paper, we introduce several estimators of the marginal posterior and test their performance on the radial velocities for HD 88133 published in Fischer et al. (2005). While our test data set consists of purely RV observations, we expect that most of our findings are also directly applicable to other dynamical planet searches (e.g., astrometric, pulsar/white dwarf timing). Other types of planet searches (e.g., transits, microlensing, direct imaging) likely present different challenges. Nevertheless, the challenge of estimating marginal posterior probabilities is quite general. Thus, we expect our finding may provide insights into methods for Bayesian model selection in other areas of astronomy and statistics.

2.1. Sampling from Prior

Basic Monte Carlo The most obvious basic Monte Carlo (BMC) estimator of $m(\vec{v})$ is based on drawing $\vec{\theta}_i$ from the prior and discretizing the integral in Eqn. 3 to create the estimator $\hat{m}_{BMC}(\vec{v}) = \sum_{i=1}^n L(\vec{\theta}_i)/n$. Unfortunately, the very large parameter space makes this totally impractical, even for a single planet system. Using the prior in Table 1, we drew over 10^9 samples, but $\hat{m}_{BMC}(\vec{v})$ underestimated $m(\vec{v})$ by orders of magnitude while the internal error estimate suggested a random error of 2%. This is due to the fact that not a single sample landed in the dominant peak in the likelihood (see Fig. 1, right).

Restricted Monte Carlo The BMC estimator can be easily modified by sampling from only a small subset of the prior. Using MCMC, we sample from the posterior, select one model parameter for investigation and then marginalize over all the remaining parameters. Then, we use the marginalized posterior distributions to identify the subset of parameter space with non-negligible probability (e.g., 99.9% credible interval). Using this technique, we identified a region with volume, V_{RMC} , $\simeq 2 \times 10^8$ times less than the volume of the prior distribution, V_{Prior} . Then, we can estimate,

$$\hat{m}_{RMC}(\vec{v}) = \frac{V_{RMC}}{V_{Prior}} \sum_{i=1}^n L(\vec{\theta}_i)/n, \quad (4)$$

where $\vec{\theta}$ are drawn from a distribution proportional to the prior over the restricted range of parameter values and zero elsewhere. For our test case, the RMC estimator provides a reasonable estimate of $m(\vec{v})_{RMC}$ (see Fig. 2, top, solid curve). However, this estimator has several shortcomings. First, it is biased due to the fact that it includes the probability coming from only one hypercube of parameter space. If we choose a large subvolume, then the estimator converges slowly, since most samples miss the high likelihood regions. If we choose a small subvolume, then we may neglect a significant region of probability outside our hypercube. These problems are exacerbated for data sets where there are significant correlations between parameters and/or many model parameters. While we were able to choose an effective subvolume for the test data set, the estimator converged slowly, requiring $\sim 2 \times 10^6$ samples to reach 5% accuracy. Finally, we note that prohibitively large subvolumes can be necessary for other data sets that allow a broader range of orbital solutions and/or significant correlations between parameters.

Partial Linearization & Laplace Approximation In the approximation of circular orbits, the predicted velocity can be written as a linear function of functions of all the model parameter except P and s . Thus, for given values of P and s , there is a single global maximum of the likelihood that can be quickly located by solving a set of linear equations. We can analytically integrate over the remaining model parameters (K_i , M_i , C_j) using the Laplace approximation by evaluating the likelihood at the global maximum (for a given P and s) and the Fischer information matrix evaluated at that point (for details see Cumming 2004; Ford 2006b). For a system with N_p planets, this leaves only $1+N_p$ dimensions to be explored by brute force Monte Carlo, making the Monte

Carlo integration dramatically more efficient. For small eccentricities, the velocity perturbation due to a planet can be approximated by a series expansion in eccentricity. If we use the $O(e^1)$ (epicycle) approximation, then the predicted velocity can again be linearized over all model parameters except P and s , allowing the this technique to efficiently consider for small eccentricities. We choose a test case to have a modest velocity amplitude and small eccentricity, so that the circular and epicycle approximations provide reasonable approximations for the radial velocity perturbations due to HD 88133b. Thus, we expected partial linearization would provide at least an order of magnitude estimate of the true marginal posterior probability, as well as a point of reference for comparing other estimators. Indeed, a comparison of this estimator to the more sophisticated estimators of §2.3-2.5, we find that this estimator of $m(\vec{v})$ shows a systematic bias (Fig. 2, top, long-dashed curve), likely due to the Laplace and the epicycle approximations. When the linear approximation to the velocity is not adequate, then a similar technique can be used, but the predicted velocity is non-linear in the parameters P_i , e_i , M_i , and s , so the partial linearization leaves $1 + 3N_p$ dimensions to be explored by brute force. While partial linearization is useful for analyzing systems with one planet (e.g., Ford 2006b), it rapidly becomes computationally impractical for multiple planet systems.

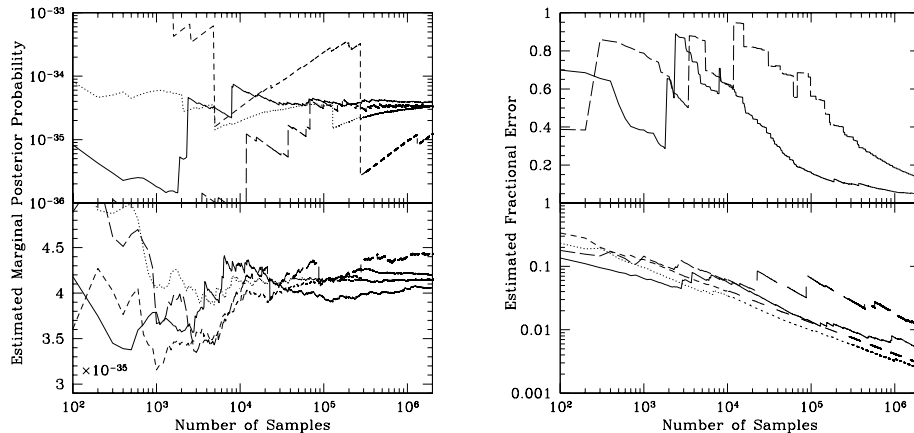


Figure 2. Comparison of several estimators of the marginal posterior probability for single planet models and the 17 RV observations of HD88133 shown in Fig. 1. Left: Estimators of the marginal probability for a one-planet model. Right: Internally estimated standard deviation of each estimator. The line styles indicate the algorithms used for each estimator: Restricted Monte Carlo (top, solid), Partial Linearization (top, long-dash), Harmonic Mean (top, short-dash), Gelfand & Dey with Partial Linearization (top, dotted), Importance Sampling from single Normal (bottom, dotted), Importance Sampling from Mixture of Normals (bottom, solid), Gelfand & Dey with Mixture of Normals (bottom, long-dash), Ratio Estimator (bottom, short-dash).

2.2. Sampling from Posterior

Given the serious difficulties in sampling from the prior, we proceed to consider estimators of the marginal posterior that sample from alternative distributions.

MCMC provides a computationally efficient tool for sampling from the posterior. Since a Bayesian analysis will typically use MCMC to generate a sample from the posterior for the purposes of parameter estimation, we investigate estimators that can use such a sample to calculate $m(\vec{v})$.

Harmonic Mean Newton & Raftery (1994) propose the estimator $\hat{m}_{NR}(\vec{v}) = n / \sum_{i=1}^n 1/L(\vec{\theta}_i)$. Unfortunately, this estimator displays extremely poor convergence properties (Fig. 2, left, top, short-dash curve), as it has an infinite variance. Newton & Raftery (1994) suggested sampling from a mixture of the posterior and prior to obtain an estimator with finite variance, but we found similarly poor performance.

Weighted Harmonic Mean & Partial Linearization Gelfand & Dey (1994) use the identity

$$[m(\vec{v})]^{-1} = \int \frac{h(\vec{\theta})}{p(\vec{\theta})L(\vec{\theta})} p(\vec{\theta}|\vec{v}) d\vec{\theta}, \quad (5)$$

where $h(\vec{\theta})$ is an arbitrary density to create an estimator for the marginal posterior probability,

$$\hat{m}_{WHM,h}(x) = n / \sum_{i=1}^n \frac{h(\vec{\theta}^i)}{p(\vec{\theta}^i)L(\vec{\theta}^i)}, \quad (6)$$

where θ^i are drawn from the posterior. This estimator should perform well when $h(\vec{\theta})$ approximates the posterior in regions of high probability, and it has finite variance when the tails of $h(\vec{\theta})$ decay faster than the tails of $p(\vec{\theta})L(\vec{\theta})$ (see Carlin & Louis 2000, §6.3.1). We set $h(\vec{\theta})$ equal to $p_e(\vec{\theta}|\vec{v}) = p(\vec{\theta})L_e(\vec{\theta}) / \int d\vec{\theta} p(\vec{\theta})L_e(\vec{\theta})$, where $L_e(\vec{\theta})$ is a likelihood computed as in Eqn. 1, but replacing the Keplerian model with the epicycle approximation for computing the velocity perturbation of each planet and $p_e(\vec{\theta}|\vec{v})$ is the posterior under this approximation. The normalization is calculated using partial linearization & the Laplace approximation as discussed in §2.1.3. Unfortunately, we find that even this approximation displays poor convergence in our test case (Fig. 2, left, top, dotted curve).

2.3. Simple Importance Sampling

Given the poor convergence properties of the previous estimators based on sampling from the prior and posterior densities, we investigate estimating $m(\vec{v})$ via importance sampling. Importance sampling requires that we specify a properly normalized density $h(\vec{\theta})$ which we can both evaluate at any $\vec{\theta}$ and sample from efficiently. We estimate $m(\vec{\theta})$ with

$$\hat{m}_{IS,h}(\vec{\theta}) = \frac{1}{n} \sum_{i=1}^n \frac{p(\vec{\theta}^i)L(\vec{\theta}^i)}{h(\vec{\theta}^i)}, \quad (7)$$

where $\vec{\theta}^1, \dots, \vec{\theta}^n$ are drawn from $h(\vec{\theta})$. We choose $h(\vec{\theta}) = N(\vec{\vartheta}_o, \Sigma)$, where N is the multivariate normal distribution in a set of transformed model parameters, $\vec{\vartheta}(\vec{\theta})$ (Ford 2006a). We use the transformation $\vec{\vartheta}(\vec{\theta}) = \{\log P, K \cos(\omega + M)\}$,

$K \sin(\omega + M)$, $e \cos \omega$, $e \sin \omega$, C , $\log s$ } to help reduce non-linear correlations between model parameters. We use a sample from the posterior to determine the location, $\vec{\vartheta}_o$, and sample covariance, Σ' , in the transformed coordinates. We find that the variance of this estimator is reduced if we scale the sample covariance matrix by a factor $\varsigma \simeq 2$ to obtain $\Sigma = \varsigma \Sigma'$, the covariance matrix used in the importance sampling density.

In our test case, $\hat{m}_{IS,N}$ appears to be a very robust and efficient estimator for this data set (Fig. 2, bottom, dotted curve). Indeed, there would be no need to pursue more sophisticated estimators, if $\hat{m}_{IS,h}(\vec{\theta})$ performed so well on all data sets. However, we are concerned that this estimator will not be viable for other data sets where the posterior can not be well approximated by a single multivariate normal distribution. This is likely to occur in systems with long orbital periods (see Ford 2005, Fig. 1), small data sets, and/or when the velocity amplitude is small. The posterior typically is dominated by a single peak for most published RV data sets (almost by definition, since a data set that can be explained by two qualitatively different orbital solutions would not be considered to have discovered the planet and is unlikely to be published). However, if Bayesian model selection is to be used for deciding when a planet has been detected or as a part of Bayesian adaptive design, then it will be necessary to analyze data sets before the posterior is so strongly peaked that it can be well approximated by a single normal distribution. Therefore, we proceed to develop a more sophisticated importance sampler that can be more robust when analyzing such data sets.

2.4. Sampling from a Mixture Density

Basic Importance Sampling In an effort to develop an importance sampling density suitable for application to a general RV data set, we consider a mixture of multivariate normal distributions. We assume that MCMC has already been used to obtain a good sample $(\vec{\theta}^1, \dots, \vec{\theta}^{n_t})$ from the posterior and use this to construct an importance sampling density,

$$g(\vec{\theta}) = \frac{1}{n_c} \sum_{j=1}^{n_c} g_j(\vec{\theta}), \quad (8)$$

where we have randomly chosen $n_c = 100$ samples to be removed from the original posterior sample and to be used as the locations for the mixture components, $g_j(\vec{\theta})$. We choose each mixture component to be a multivariate normal distribution, $g_j(\vec{\theta}) = N(\vec{\vartheta}(\vec{\theta}) | \vec{\vartheta}(\vec{\theta}^j), \Sigma_j)$, where we must determine a covariance matrix for each g_j using the posterior sample. First, we compute $\vec{\rho}$, defined to be a vector of the sample standard deviations for each of the components of $\vec{\vartheta}$, using the posterior sample. Next, we define the distance between the posterior sample $\vec{\theta}^i$ and the center of $g_j(\vec{\theta})$, $d_{ij}^2 = \sum_k (\vartheta_k(\vec{\theta}^i) - \vartheta_k(\vec{\theta}^j))^2 / \rho_k^2$, where k indicates the element of $\vec{\vartheta}$ and $\vec{\rho}$. We draw another random subset of $n_{cv} = 50n_c$ samples from the original posterior sample (without replacement), select the n_{cv}/n_m posterior samples closest to each mixture component and use them to calculate the covariance matrix, Σ'_j , for each mixture component. We set $\Sigma_j = \varsigma \Sigma'_j$, and $\varsigma = 1$. Thus, we have developed an automated algorithm for using a posterior

sample to construct an importance sampling density, $g(\vec{\theta})$. Since the posterior sample is assumed to have fully explored the posterior, $g(\vec{\theta})$ should be quite similar to the posterior in all regions of significant probability, provided that we use enough mixture components.

We use $g(\vec{\theta})$, n_s samples from the remainder of our posterior sample, and deterministic mixture sampling to compute the estimator, $\hat{m}_{IS,g}(\vec{v})$. We find that it performs quite well in our test case (Fig. 2, bottom, solid curve). It converges nearly as rapidly as $\hat{m}_{IS,N}(\vec{v})$ and appears somewhat more robust, even for the rather simple posterior in our test case. In tests on more complex data sets, we find that $\hat{m}_{IS,g}(\vec{v})$ can be significantly more robust than $\hat{m}_{IS,N}(\vec{v})$ for data sets with somewhat less well constrained posterior PDFs, but both estimators perform poorly on other data sets with very diffuse posterior PDFs. We speculate that our method for choosing the mixture components could be replaced by a more sophisticated algorithm that might result in a superior importance sampling densities for challenging data sets.

Defensive Importance Sampling Despite the success of $\hat{m}_{IS,g}$, we have some concerns about the robustness of $\hat{m}_{IS,g}$ for high dimensional parameter spaces (e.g., analyzing systems with several planets). As the number of model parameters increases, it will become increasingly difficult to avoid $p(\vec{\theta})L(\vec{\theta})/g(\vec{\theta})$ becoming unusually large for some values of $\vec{\theta}$. To prevent this we generalize our importance sampling density to include a component from the prior, by defining $g_0(\vec{\theta}) = p(\vec{\theta})$ and $g^*(\vec{\theta}) = \sum_{j=0}^{n_c} g_j(\vec{\theta})/(n_c + 1)$, Following Owen & Zhou (2000), we combine this mixture density with control variables to obtain the estimator

$$\hat{m}_{DIS,g^*,\vec{\beta}}(\vec{v}) = \frac{1}{n_s} \sum_{i=1}^{n_s} \frac{p(\vec{\theta}^i)L(\vec{\theta}^i) - \sum_{j=0}^{n_c} \beta_j g_j(\vec{\theta}^i)}{g^*(\vec{\theta}^i)} + \sum_{j=0}^{n_c} \beta_j, \quad (9)$$

which is valid for any choice of $\vec{\beta}$. To minimize the variance of this estimator, we set $\vec{\beta} = \vec{\beta}^*$, where $\vec{\beta}^*$ is determined by least squares fitting to the linear system of n_s equations

$$\sum_{j=0}^{n_c} \left(\frac{g_j(\vec{\theta}^i)}{g^*(\vec{\theta}^i)} \right) \beta_j^* = \frac{p(\vec{\theta}^i)L(\vec{\theta}^i)}{g^*(\vec{\theta}^i)} \quad (10)$$

Owen & Zhou (2000) show that this estimator is never worse than an estimator based on any subset of the mixture components. In practice, we need n_s to be large to have small variance, but it is not practical to solve the linear system of equations with $n_s \simeq 10^{5-7}$. Therefore, we repeatedly solve for $\vec{\beta}$ using subsets of $n_r \ll n_s$ posterior samples and average the results to estimate $\vec{\beta}^*$. The resulting estimator $\hat{m}_{DIS,g^*,\vec{\beta}^*}(\vec{v})$ is at least as good as $\hat{m}_{IS,g}(\vec{v})$ and is expected to be considerably more robust. In our test case, the estimators $\hat{m}_{IS,g}(\vec{v})$ and $\hat{m}_{DIS,g^*,\vec{\beta}^*}(\vec{v})$ follow each so closely that the curves would be indistinguishable in Fig. 2 (bottom, solid curve). This is because the values of β_j^* are roughly comparable for all components with $j \geq 1$, while β_0 (the prior component) is orders of magnitude less than the other β_j . This reflects the fact that $g(\vec{\theta})$, our mixture of $n_c = 100$ multivariate normal distributions, was sufficient to

accurately approximate the posterior density. While $\hat{m}_{DIS,g^*,\vec{\beta}^*}(\vec{v})$ is somewhat more computationally expensive, we still prefer it to $\hat{m}_{IS,g}(\vec{v})$, since it should be more robust. Further, if $g(\vec{\theta})$ was inadequate, then β_0^* would increase, alerting us to the potential weakness of $g(\vec{\theta})$.

Weighted Harmonic Mean We now reconsider the estimator of Gelfand & Dey (1994), but using the mixture, $g(\vec{\theta})$, for the weight function h . The resulting estimator $\hat{m}_{WHM,g}(\vec{v})$ can also be thought of as the reciprocal of an estimator of $g(\vec{\theta})/(p(\vec{\theta})L(\vec{\theta}))$ using importance sampling from the (unnormalized) posterior. When using the estimator $\hat{m}_{WHM,g}(\vec{v})$, the denominator for each term in the summation contains $p(\vec{\theta})L(\vec{\theta})$ evaluated at points sampled from the posterior, so the limit to the variance of this estimator will be the size (and quality) of the sample from the posterior. This seems acceptable, since these considerations will limit any estimate of the marginal likelihood based on a sample from the posterior. Further, this seems more attractive than algorithms which place the importance sampling density in the denominator, since that could result in areas with sparse coverage (e.g., due to high dimensionality) dominating the summation. We show the performance of $\hat{m}_{WHM,g}(\vec{v})$ in Fig. 2, bottom, long-dashed curve. While this estimator performs reasonably well, it has a larger variance and appears to be converging more slowly than $\hat{m}_{IS,g}$ for our test case. Additionally, We find that this estimator is particularly sensitive to the choice of ς and rapidly degrades if ς is too large or too small.

2.5. Sampling from Multiple Densities

Ratio Estimator We present a new estimator (Berger, private communication), based on the identity

$$m(\vec{v}) = \int L(\vec{\theta})p(\vec{\theta})d\vec{\theta} = \frac{\int p(\vec{\theta})L(\vec{\theta})h(\vec{\theta})d\vec{\theta}}{\int h(\vec{\theta})p(\vec{\theta}|\vec{v})d\vec{\theta}}. \quad (11)$$

The key insight is to approximate the numerator by drawing a sample $\tilde{\theta}^1, \dots, \tilde{\theta}^{n'_s}$ from $h(\vec{\theta})$ and to approximate the denominator by drawing a sample $\tilde{\theta}^1, \dots, \tilde{\theta}^{n_s}$ from the posterior (e.g., via MCMC). This yields the ratio of estimators,

$$\hat{m}_{RE,h}(\vec{v}) = \frac{\frac{1}{n'_s} \sum_{i=1}^{n'_s} p(\tilde{\theta}^i)L(\tilde{\theta}^i)}{\frac{1}{n_s} \sum_{i=1}^{n_s} h(\tilde{\theta}^i)}. \quad (12)$$

This estimator seems particularly promising, since both the numerator and denominator are separate sums and there is no risk of a small denominator leading to a large variance, as in importance sampling. If we combine this estimator with the $g(\vec{\theta})$, the mixture of normal distributions used in §2.4. (again using a distinct subsample from the posterior for constructing $g(\vec{\theta})$), then we obtain the estimator $\hat{m}_{RE,g}$. In our test case, the numerator converges significantly more rapidly than the denominator, and so we choose $n'_s = n_s/10$ with minimal impact on the variance of the estimator. This estimator performs very well in our test case (Fig. 2, bottom, short-dashed curve). It converges as rapidly

as any of the other estimators that we considered, with the possible exception of importance sampling from a single normal distribution. Further $\hat{m}_{RE,g}(\vec{v})$ appears to be quite robust, in that it does not display sudden jumps when a single additional sample significantly changes the value of the estimator, as is more common with most of the other estimators. Unfortunately, we found that this estimator was less accurate on more complex test cases, yet it showed no warning signs that the estimator had not converged, even after $\sim 10^7$ samples.

Parallel Tempering Gregory (2005a) introduced the method of parallel tempering for estimating the marginal posterior probability for extrasolar planet observations. In parallel tempering, several Markov chains are run in parallel, each with a slightly different target density, $\pi_\beta(\vec{\theta}) = p(\vec{\theta}|\mathcal{M})p(\vec{v}|\vec{\theta}, \mathcal{M})^\beta$, where β is an inverse temperature parameter that varies between 0 and 1. In the parallel tempering algorithm, each Markov chain typically evolves according to the usual candidate transition PDFs, but periodically the algorithm proposes an exchange of states between two Markov chains that have slightly different values of β . The “high temperature” Markov chains ($\beta \simeq 0$) will explore a very broad region in parameter space and can help the “coldest” Markov chain ($\beta = 1$) to sample from the full posterior distribution, even when there are narrow and widely separated peaks in the posterior distribution (Gregory 2005b). In principle, the marginal posterior probability can also be calculated from the ensemble of Markov chains, using

$$\hat{m}_{PT}(\vec{v}) = p(\mathcal{M}) \exp \left\{ \int d\beta \sum_{i=1}^{n_s} \log [p(\vec{v}|\vec{\theta}_{i,\beta}, \mathcal{M})] \right\}, \quad (13)$$

where $\vec{\theta}_{i,\beta}$ is the i th state in the Markov chain with target distribution $\pi_\beta(\vec{\theta})$, and the integral over β is to be approximated by an appropriate weighted sum over the values of β used by the various Markov chains.

We show the performance of $\hat{m}_{PT}(\vec{v})$ using 32 tempering levels for the test data set in Fig. 3. Based on five completely independent realizations of the parallel tempering algorithm, we found that four provided a reasonable estimate of the $m(\vec{v})$, but one set of chains resulted in an estimate roughly twice as large as any other estimator tested. If this set of Markov chains had been the only realization, none of the usual diagnostics would have recognized that it had not yet converged. Therefore, we feel that more work is needed to understand the properties of marginal posterior estimates obtained from parallel tempering. If the sensitivity of the estimator were due to the slow convergence of the highest temperature chains ($\beta \simeq 0$), then their contribution to the integral over β could be approximated by an analytic sampler from the prior (corresponding to $\beta = 0$). However, we have verified that for our test case (see Table 2), the Markov chains with very small values of β make only minor contributions to the integral over β . The second column of Table 2 gives the fractional error that would result if this decade of β was not included and thus indicates the sensitivity of the result to that decade. Therefore, we suspect that the chains limiting the accuracy of $\hat{m}_{PT}(\vec{\theta})$ have $\beta > 10^{-3}$.

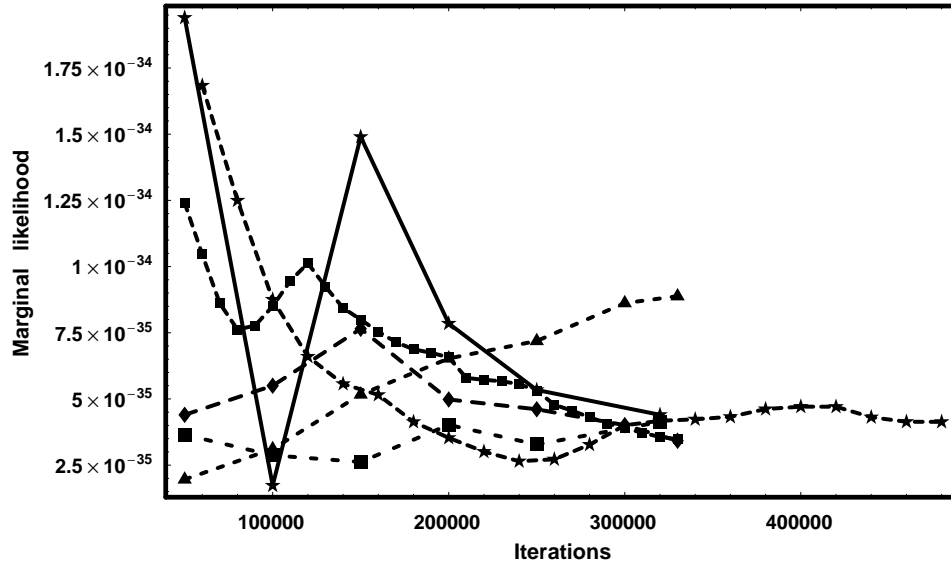


Figure 3. The estimate of the marginal probability for a one-planet model and the 17 RV observations of HD88133 shown in Fig. 1 using the parallel tempering method of Gregory (2005a) as a function of the number of iterations in each of the Markov chains. Each of the lines corresponds to a completely independent set of 32 Markov chains. Since each curves is based on Markov chains with 32 different values of β , even the parallel tempering simulations that stopped after 320,000 iterations required roughly five times more likelihood evaluations than the each of the estimators shown in Fig. 2.

Table 2. Fractional error versus β for the results shown in Fig. 3.

β range	Fractional error
$1.0 - 10^{-1}$	3.83×10^{28}
$10^{-1} - 10^{-2}$	5.20×10^5
$10^{-2} - 10^{-3}$	4.02
$10^{-3} - 10^{-4}$	0.54
$10^{-4} - 10^{-5}$	0.30
$10^{-5} - 10^{-6}$	0.26
$10^{-6} - 10^{-7}$	0.12
$10^{-7} - 10^{-8}$	0.02
$10^{-8} - 10^{-9}$	2×10^{-3}
$10^{-9} - 10^{-10}$	2×10^{-4}
$10^{-10} - 10^{-11}$	2×10^{-5}

2.6. Other Techniques for Model Selection

While we are encouraged by the recent progress in developing efficient and robust estimators of the marginal posterior probability, there are several additional avenues of research that might lead to even more desirable estimators. One

interesting method is based on the of nested sampling methods of Skilling (2005). Unfortunately, for the problem of radial velocity planet searches, there is no efficient way to sample only from high posterior probability regions of parameter space, as required by nested sampling. As a result, we can only apply nested sampling if we employ the very inefficient method of rejection sampling.

Another class of algorithms for estimating Bayes factors relies on sampling over the model space. Two subclasses of methods have been the subject of much research in the statistics community: reversible jump MCMC (Green 1995), and model composition MCMC (MC³) (Carlin & Chibb 1995). Unfortunately, we find that the most obvious choices of pseudopriors (e.g. Green & O’Hagan 1998) for MC³ result in very poor mixing between different models. Perhaps future research can adapt these methods to allow for more rapid mixing between models with different numbers of planets. Similarly, simplistic implementations of reversible jump methods seem unlikely to be practical, since the trial jumps into higher dimensional spaces will only land in areas of significant probability on extremely rare occasions. On the other hand, we are more optimistic about reversible jump algorithms that employ an analytic approximation to each of the posterior PDFs within the i th model ($p(\vec{\theta}|\vec{v}, \mathcal{M}_i)$) for the transdimensional steps. We envision that each of the analytic approximations could be based on mixture models constructed from a sample from $p(\vec{\theta}|\vec{v}, \mathcal{M}_i)$ obtained using conventional MCMC techniques, similar to the importance sampling densities we employed for $\hat{m}_{IS,g}(\vec{v})$.

An even more radical idea is to abandon the computation of marginal posterior probabilities in favor of some other statistic to aid in quasi-Bayesian model selection. Penalized likelihood methods such as the Akaike and Bayesian information criterion do not seem well justified when the posterior is significantly non-normal or multi-modal. Additionally, we are suspicious of any method that penalizes all parameters equally, as our model is much more sensitive to some model parameters (e.g., orbital period) than to others (e.g., eccentricity). Therefore, we are more interested in exploring methods based on the predictive distribution. Unfortunately, any of these alternative methods for model selection is somewhat arbitrary and less than ideal for the purposes of adaptively scheduling observations based on the principles of Bayesian adaptive experimental design.

3. Conclusions

In this paper, we have reviewed several methods for calculating the marginal posterior probabilities in the context of RV planet searches. On the positive side, we found that several algorithms were able to accurately calculate the marginal posterior probability for a simple test case, where there was a single dominant peak in the posterior probability distribution. However, all of the estimators based on sampling from either the prior or posterior had serious shortcomings.

The method of partial linearization can be a useful tool for rapidly computing relatively low accuracy estimates of $m(\vec{v})$ for data sets with one planet or even $\sim 1 - 3$ planets on low eccentricity orbits. However, it rapidly becomes computationally intractable when there are multiple planets with significant eccentricities. Restricted Monte Carlo ($\hat{m}_{RMC}(\vec{v})$) can be useful for planets with

large eccentricities, but is computationally feasible only once the orbital parameters are relatively well constrained. Parallel tempering is able to estimate $m(\vec{v})$ even for multimodal posterior distributions, but for our test data set $\hat{m}_{PT}(\vec{\theta})$ converged more slowly than all of the other algorithms tested (except basic Monte Carlo). For our test case, we found no regime where the harmonic mean ($\hat{m}_{NR}(\vec{v})$) or the weighted harmonic mean ($\hat{m}_{WHM,h}(\vec{v})$) would be the most desirable estimator. The new ratio estimator ($\hat{m}_{RE}(\vec{v})$) performed very well for our test case, but we recommend proceeding with caution, based on preliminary tests with more complex data sets.

Based on our tests, the most promising methods are based on importance sampling using an analytic density that mimics the posterior (e.g., $\hat{m}_{IS,N}(\vec{v})$ or $\hat{m}_{DIS,g^*,\vec{\beta}^*}(\vec{v})$). When the posterior has a single dominant peak that can be reasonably approximated by a multivariate normal distribution, then simple importance sampling ($\hat{m}_{IS,N}(\vec{v})$) provides a very efficient tool for estimating marginal posteriors. In cases where the posterior is more complex (e.g., multiple peaks and/or non-linear parameter correlations), then importance sampling can still be useful when combined with a mixture distribution based on a sample from the posterior that can be readily calculated via standard MCMC. Refinements to the basic importance sampling algorithm (e.g., $\hat{m}_{DIS,g^*,\vec{\beta}^*}(\vec{v})$) can provide increased robustness and offer a tool for diagnosing when the mixture distribution is sufficient. We hope that future research will improve our understanding of these estimator’s theoretical and real-life properties, as well as lead to additional refinements. In particular, we hope to investigate how the estimator $\hat{m}_{DIS,g^*,\vec{\beta}^*}(\vec{v})$ performs on more widely dispersed posterior distributions and on higher dimensional problems (e.g., multiple planet systems).

In a sense, we can consider the problem of Bayesian model selection to have been reduced to the problem of constructing an analytic approximation to a probability density based only on a set of samples from the distribution. Unfortunately, we recognize our algorithm for constructing importance sampling densities is not yet sufficiently robust to be applied generally. Therefore, we would like to see additional research that would improve the robustness and computational efficiency of these algorithms. Fortunately, we recognize several ways our current algorithm could be improved. For example, rather than centering the mixture components on random samples from the posterior, it might be possible to make do with a smaller number of mixture components. Perhaps methods making use of Voronoi tessellations and/or quasi-Monte Carlo methods could be beneficial in constructing good mixture distributions with fewer components, improving the computational efficiency of these methods.

Finally, we note that this field is still young, and additional research is needed to explore a wide range of methods for estimating $m(\vec{\theta})$, including methods on importance sampling, parallel tempering, reversible jump MCMC, MC³, and nested sampling.

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