An Interferometric Search for Bright Companions to 51 Pegasi

A.F. Boden[1], G.T. van Belle[1], M.M. Colavita[1], P.J. Dumont[1], J. Gubler[2], C.D. Koresko[3], S.R. Kulkarni[3], B.F. Lane[3], D.W. Mobley[1], M. Shao[1], J.K. Wallace[1] (The PTI Collaboration)

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[1]Jet Propulsion Laboratory, California Institute of Technology

[2]University of California, San Diego

[3]Palomar Observatory, California Institute of Technology

ABSTRACT

We report on a near-infrared, long-baseline interferometric search for luminous companions to the star 51 Pegasi conducted with the Palomar Testbed Interferometer. Our data is completely consistent with a single-star hypothesis. We find no evidence to suggest a luminous companion to 51 Pegasi, and can exclude a companion brighter than a ΔK of 4.27 at the 99% confidence level for the 4.2-day orbital period indicated by spectroscopic measurements. This ΔK corresponds to an upper limit in the companion M_K of 7.30, in turn implying a main-sequence companion mass less than 0.22 $M_\odot$.

Subject headings: binaries: spectroscopic — planetary systems — stars: individual (51 Pegasi) — techniques: interferometric

1. Introduction

The recent inference of a planetary-mass gravitational companion to the star 51 Pegasi (HD 217014) from apparent radial velocity variation by Mayor & Queloz (1995) has subjected this otherwise unremarkable star to remarkable scrutiny. The Mayor and Queloz result was quickly verified by several groups with similar or higher-resolution spectroscopic techniques (c.f. Marcy et al 1997). However, there has been no other evidence for a companion, e.g. precision photometric monitoring has failed to show evidence for eclipses (Henry et al 1997), and there is a significant lack of x-ray flux from the system compared to binary systems with similar periods (Pravdo et al 1996). Further, 51 Peg's G5V spectral classification has become mildly controversial (e.g. Houk 1995, who argues for a G2-3V), as has its physical size (e.g. Hatzes et al 1997, Henry et al 1997).

A planetary-mass companion in a 4.2 day orbit around a solar-mass 51 Peg would have an orbital semi-major axis of approximately 0.05 AU (Marcy et al 1997), slightly more if the companion were more massive. At a distance of 15.4 $\pm$ 0.2 pc (Perryman et al 1996), the approximate maximum primary-companion angular separation would be 3.5 millarcseconds (mas). Such an angular separation is well below resolution limits for current conventional imaging technology, but is accessible to optical and near-infrared interferometry. As only the lower mass limit is set by the spectroscopic results, it is possible the companion is significantly more massive – perhaps even a low-mass star. We have therefore studied 51 Peg with the Palomar Testbed Interferometer (PTI) in an attempt to detect the putative companion if it is indeed sufficiently luminous. PTI is a 110m-baseline interferometer operating at K-band (2 – 2.4 μm) located at Palomar Observatory, and described in detail elsewhere (Colavita et al 1994). The minimum PTI fringe spacing is roughly 4 mas at the sky position of 51 Peg, making a (sufficiently) luminous companion readily detectable.

2. Experiment Design

The observable used for these observations is the fringe contrast or *visibility* (squared) of an observed brightness distribution on the sky. In the limit that the putative 51 Peg companion is dim (or non-existent), 51 Peg itself would appear as a single star, exhibiting visibility modulus (and trivially, visibility squared) given in a uniform disk model by:

$$V^2 = (V)^2 = \left(\frac{2\,J_1(\pi B\theta/\lambda)}{\pi B\theta/\lambda}\right)^2 \tag{1}$$

where J_1 is the first-order Bessel function, B is the projected baseline vector magnitude at the star position, θ is the apparent angular diameter of the star, and λ is the center-band wavelength of the interferometric observation. However, if the putative 51 Peg companion were in fact luminous enough to be detected by the interferometer, the expected squared visibility in a narrow bandpass would be given by:

$$V^2 = \frac{V_1^2 + V_2^2\,r^2 + 2\,V_1\,V_2\,r\,\cos(\frac{2\pi}{\lambda}\,\mathbf{B}\cdot\mathbf{s})}{(1+r)^2} \tag{2}$$

where V_1 and V_2 are the visibility moduli for 51 Peg and the putative companion alone as given by Eq. 1, r is the apparent brightness ratio between the 51 Peg primary and companion, $\mathbf{B}$ is the projected baseline vector at the 51 Peg position, and $\mathbf{s}$ is the primary-companion angular separation vector on the plane of the sky.

The key to detecting a companion to 51 Peg in PTI data is to reliably determine the stability of the V^2 measured on 51 Peg. Without a luminous companion Eq. 1 predicts a stable value of the V^2 observable on 51 Peg (with small variations due to baseline projection effects with varying hour angle on the source). Conversely, in the presence of a luminous companion Eq. 2 predicts sinusoidal excursions in V^2 as the system evolves and the Earth rotates; a three-magnitude fainter companion would produce roughly 20% peak-to-peak excursions in V^2. A preliminary examination of data from 1996 suggested significant V^2 variations in 51 Peg (Pan 1997). The PTI instrument configuration for the 1997 observations reported here incorporates compensation for spatially-varying instrument vibrations, as well as spatial filtering to improve the visibility measurements, both of which affected the 1996 data. In the analysis presented here we have placed

an emphasis on choosing calibration sources and techniques that minimize potential instrumental or environmental effects; namely we have required calibration observations that are in close spatial (sky) and temporal proximity to the 51 Peg observations. Due to a limiting K-magnitude of ~ 5 (Colavita et al 1994) this calibration strategy forces us to use slightly resolved calibration sources, making the absolute calibration of the V^2 difficult to determine. In the present work we have estimated the apparent diameter of the calibration objects with respect to a model diameter for 51 Peg (Table 1), and then assessed the V^2 stability of 51 Peg and its calibrators by inter-comparison. Such a strategy can say nothing about the actual apparent diameter of 51 Peg; we defer this question to a separate publication.

3. Observations

The star 51 Pegasi and at least one nearby calibration object were included in the PTI observing program on 18 nights from July 19 through November 23, 1997. Because we have noted significant systematic effects in measured visibilities over large sky separations, in this analysis we have limited our attention to 51 Peg data calibrated by two nearby calibrators, HD 215510 and HD 211006, with similar K-band brightness (3.96) as 51 Peg (Campins, Rieke, & Lebofsky 1985). The relevant parameters of the calibration objects are summarized in Table 1. These calibration objects show no previous evidence of multiplicity or photometric variability, as well as no evidence of multiplicity in our data (see below). Both of these objects are resolved by our long baseline, hence the absolute calibration of our data depends on the calibrator diameters. Apparent diameters for the calibration objects were estimated by single-star fits to V^2 sequences calibrating the calibration objects with respect to a single-star model 51 Peg with model diameter of 0.72 ± 0.06 mas implied by $R_{51P} = 1.2 \pm 0.1\ R_{\odot}$ (adopted by Marcy et al 1997) and 65.1 ± 0.76 mas Hipparcos parallax (Perryman et al 1996). The hypothesis fits themselves are discussed in §5. This procedure is sufficient in a search for luminous companions to 51 Peg, but leaves open the question of 51 Peg's apparent diameter.

Raw V^2 measurements were made through methods described in Colavita (1998). An example

Object Name	Spectral Type	Star Mag	51 Peg Separation	Diam. WRT Model 51 Peg
HD 215510	G6III	6.3 V 3.9 K	3.1°	0.85 ± 0.06
HD 211006	K2III	5.9 V 3.4 K	13°	1.08 ± 0.05

Table 1: 1997 PTI 51 Peg Calibration Objects Considered in our Analysis. The relevant parameters for our two calibration objects are summarized. The apparent diameter values are determined by a fit to our V^2 data calibrated with respect to a single-star model 51 Peg using a model diameter of 0.72 ± 0.06 mas (Marcy et al 1997, Perryman et al 1996, see Table 2).

of the raw data from one night's (97236 – 8/24/97) observation of 51 Peg and a nearby calibrator (HD 215510) is given in Figure 1.

4. Calibrated Datasets

The calibration of 51 Peg V^2 data is performed by estimating the interferometer system visibility using calibration sources with model angular diameters, and then normalizing the raw 51 Peg visibility by that system visibility estimate in order to estimate the V^2 measured by an ideal interferometer at that epoch. In this letter we consider 51 Peg datasets calibrated by the two nearby calibration objects (Table 1). We have prepared two different calibrated 51 Peg datasets:

- *AND Dataset*: This dataset requires at least one observation ("scan") on both nearby calibrators within a ± one-hour calibration time window (all calibration measurements within the time window are averaged together). This dataset contains 105 calibrated scans on 51 Peg over 13 nights spanning a total time interval of 123 days.
- *OR Dataset*: This dataset requires at least one scan on either of the nearby calibrators within the ± one-hour calibration time window as above. This dataset contains 146 scans

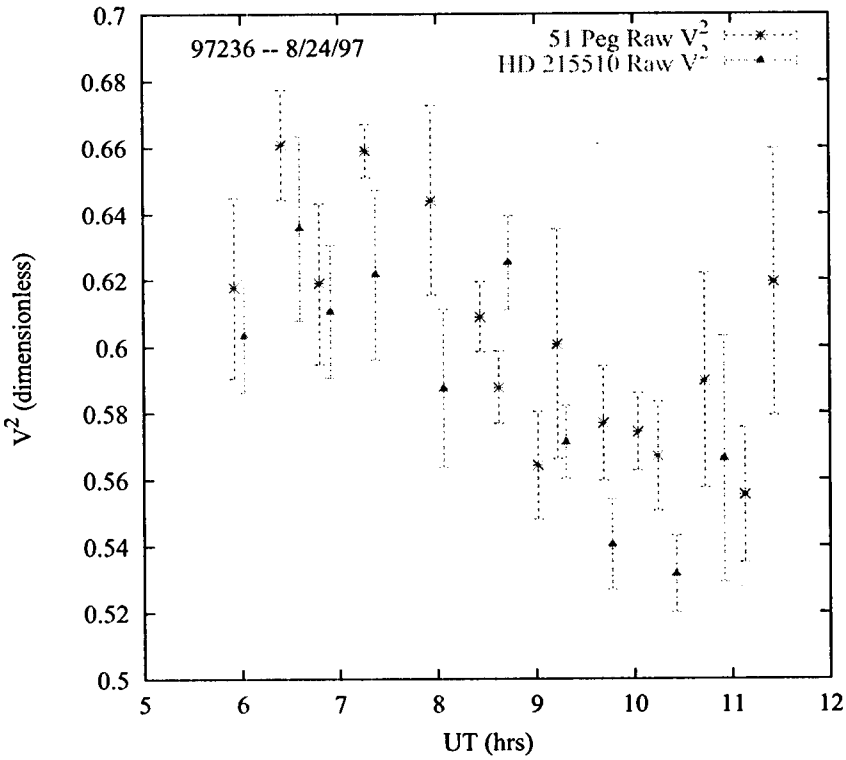

Fig. 1.— Raw V^2 Data for 51 Peg and Calibrator. This plot shows raw V^2 data from a particular night (97236 – 8/24/97) for 51 Peg and a nearby calibrator (HD 215510, 3.1° away). The V^2 data has been averaged over the 120-second observations, and the sample standard deviation about the mean in each observation is indicated by the error bars. Both 51 Peg and the calibrator exhibit formally significant V^2 excursions, but both change in synchronism. This observation leads us to conclude that either instrumental or observing conditions can change on time scales of approximately one hour; we have structured our calibration procedures accordingly.

over 18 nights spanning the same time interval of 123 days. As defined the AND dataset is a proper subset of the OR dataset.

Calibrator Stability Further, as we rely on the V^2 stability of the two nearby calibration objects as references for the 51 Peg analysis, it is important to assess the relative stability of the two calibrators. Consequently, we prepared two additional datasets for each calibration object: calibrated with respect to the other calibration object (i.e. HD 215510 calibrated with respect to HD 211006 and vice versa), and one calibrated with respect to a single-star model 51 Peg itself using a model diameter of 0.72 ± 0.06 mas.

5. Analysis of Calibrated Datasets

We have analyzed the calibrated visibility datasets on 51 Peg and the calibrators themselves by fitting single-star (Eq. 1) and double-star (Eq. 2) hypotheses to the datasets, and by evaluating these hypotheses by considering goodness-of-fit (χ^2) metrics.

Single-Star Hypothesis Since a planetary-mass companion to 51 Peg would be too dim to observe with PTI, it is appropriate to fit a single-star hypothesis to the calibrated datasets for 51 Peg. To accomplish this task we have used a global non-linear least-squares fitting code that fits a single-star hypothesis as given in Eq. 1 to the input calibrated V^2 datasets on 51 Peg. The single-star hypothesis fits to our datasets are summarized in Table 2. The output of the fit to the AND dataset is depicted in Figure 2, which shows a plot of the AND dataset vs. hour angle on 51 Peg. For a single star the V^2 should follow a simple model (Eq. 1). The data exhibits good agreement with the single-star model.

There are several notable aspects to these hypothesis fits. The first is to reiterate that the best fit angular diameter estimate of 0.73 ± 0.02 mas does not constitute an independent determination of the 51 Peg angular diameter – it is just a ramification of the 0.72 mas model diameter assumed for 51 Peg in the determination of the calibrator angular diameters. We further

have quoted only statistical errors on the fit diameters as determined from the internal scatter in the V^2 measurements – systematic contributions from uncertainty in the calibrator diameters are deliberately neglected to simplify interpretation of the χ^2 results.

The second notable aspect of the single-star fits is χ^2 per degree of freedom (DOF) values that are in excellent agreement with the expected value of 1.0. The fit of the single-star model is good compared to our assumed error bars based on internal scatter of the raw V^2 data. This is somewhat suprising; while the relative weighting is reasonably well established by internal scatter, we have no reliable a priori model for the absolute scale of errors in our calibrated data. The mean absolute V^2 residual around the single-star hypothesis is slightly less than 3%. This average absolute deviation is consistent with PTI instrument performance in other analyses (Boden et al 1998), the absolute deviations seen in the calibrator data (see below), and a good indication of the level of error in our calibrated V^2 measurements in a single-star model for 51 Peg.

Also contained in Table 2 are the results from the calibrator inter-comparisons, and fits to calibrator datasets using a single-star model 51 Peg as a reference. In all cases the agreement with single-star models is good both in an absolute deviation ($|\epsilon|$) and a statistical (χ^2) sense. In particular, the results in the datasets where one calibrator is calibrating the other are consistent with the values obtained in the 51 Peg datasets. The datasets with 51 Peg as a calibration object actually result in fits to the calibrators that are slightly better than the reciprocal fits to 51 Peg. This result is reasonable, as there are more 51 Peg scans than calibrator scans, hence the system calibration is on average better determined using 51 Peg as a calibrator.

In summary, our data on 51 Peg is completely consistent with a single-star hypothesis on the scale of the observed scatter. Further, inter-comparison of the two calibrators yields fits to single-star hypotheses at roughly the same level of agreement. Nothing in our data suggests that 51 Peg is any more variable that either of the calibrators, both in absolute and statistical terms.

Binary Hypothesis To test the possibility of a luminous object (presumably an M-dwarf star) as the inferred 4.2 day period companion of 51 Peg, we conducted an experiment where we fit a

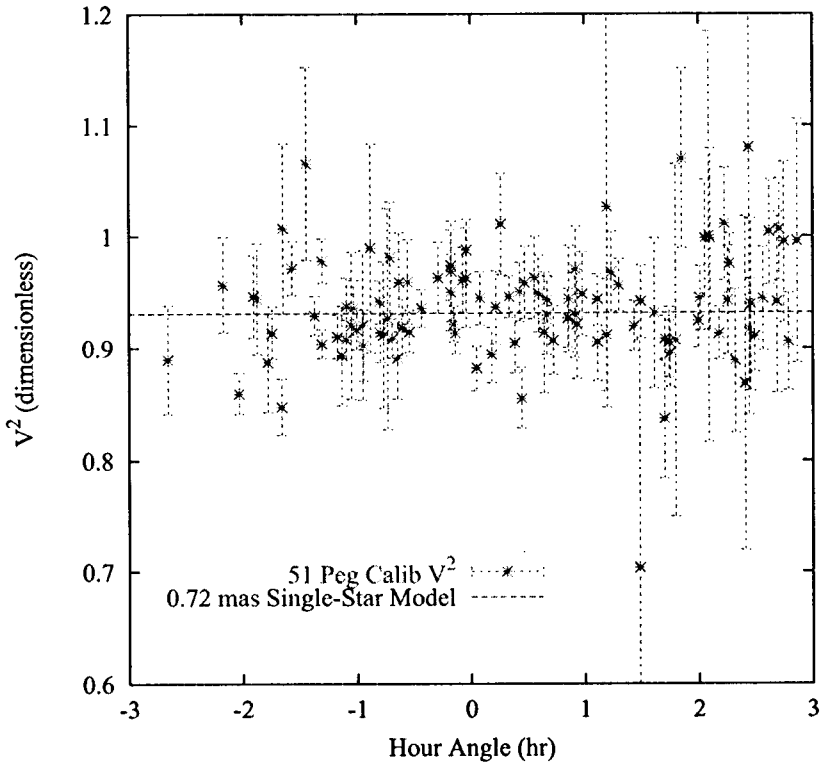

Fig. 2.— Calibrated V^2 Data vs. Hour Angle. Assuming 51 Peg is a single star, the V^2 data should follow a simple model vs. hour angle on the source. This figure shows the calibrated V^2 from the AND dataset, and the predicted V^2 vs. hour angle for a 0.72 mas diameter single star, our model for the apparent diameter of 51 Peg (Marcy et al 1997, Perryman et al 1996). The data is in good agreement with the single-star model (see Table 2).

binary orbit to the V^2 datasets, constraining the orbit to be of the appropriate (4.231 day) period, eccentricity (0), and approximately face-on orientation (inclination = 0 or π) to be consistent with the high-quality radial velocity data for the system (e.g. Marcy et al 1997). We performed this fitting procedure over an input grid of semi-major axes and K-band intensity ratios that included the values of a hypothetical M-dwarf companion in a 4.2 day orbit. For a given semi-major axis and intensity ratio, we allowed the fit to solve for the optimal orbital phase parameter and primary angular diameter. Initial values for the angular diameters for the primary and hypothetical secondary were set at our best-fit single-star value, and main-sequence model value for an M3V spectral type at the Hipparcos parallax distance, respectively. We used this procedure to map the χ^2 surface in the subspace of semi-major axis and intensity ratio.

Figure 3a shows the result of such a fitting procedure applied to the AND dataset. This figure depicts the χ^2/DOF surface over values of the semi-major axis between 0.01 and 0.16 AU (projected separations between 1 and 10 mas) and intensity ratios between 1 and 7 (K) magnitudes. Figure 3a shows the surface and a contour map displayed on a horizontal plane below the surface. At 7 magnitudes difference we are effectively testing the single-star hypothesis against the dataset, and the binary fit reproduces the χ^2/DOF seen in the corresponding single-star hypothesis fit. The apparent lack of a significant minima in the surface is striking, indicative that there is no pattern in the data which matches the combined set of orbital constraints and a 4.2-day period. With decreasing relative magnitude (a brighter companion) we see rapidly increasing fit residuals, independent of hypothetical semi-major axis.

With 105 degrees of freedom one-sigma excursions in the χ^2/DOF around 1.0 are expected to be roughly 0.14. Because we are uncertain as to the absolute level of error on individual V^2 points, we have scaled the χ^2/DOF significance contours to match the χ^2/DOF obtained in the single-star fit; this is equivalent to scaling the data errors to obtain a χ^2/DOF of 1.0 in the single-star fit, and allows us to compare the single-star and binary-star models on an equal statistical basis independent of the absolute scale of our calibrated V^2 errors. Figure 3b gives a contour map of the binary hypothesis χ^2/DOF surface with contours at the single-star fit χ^2/DOF, (scaled)

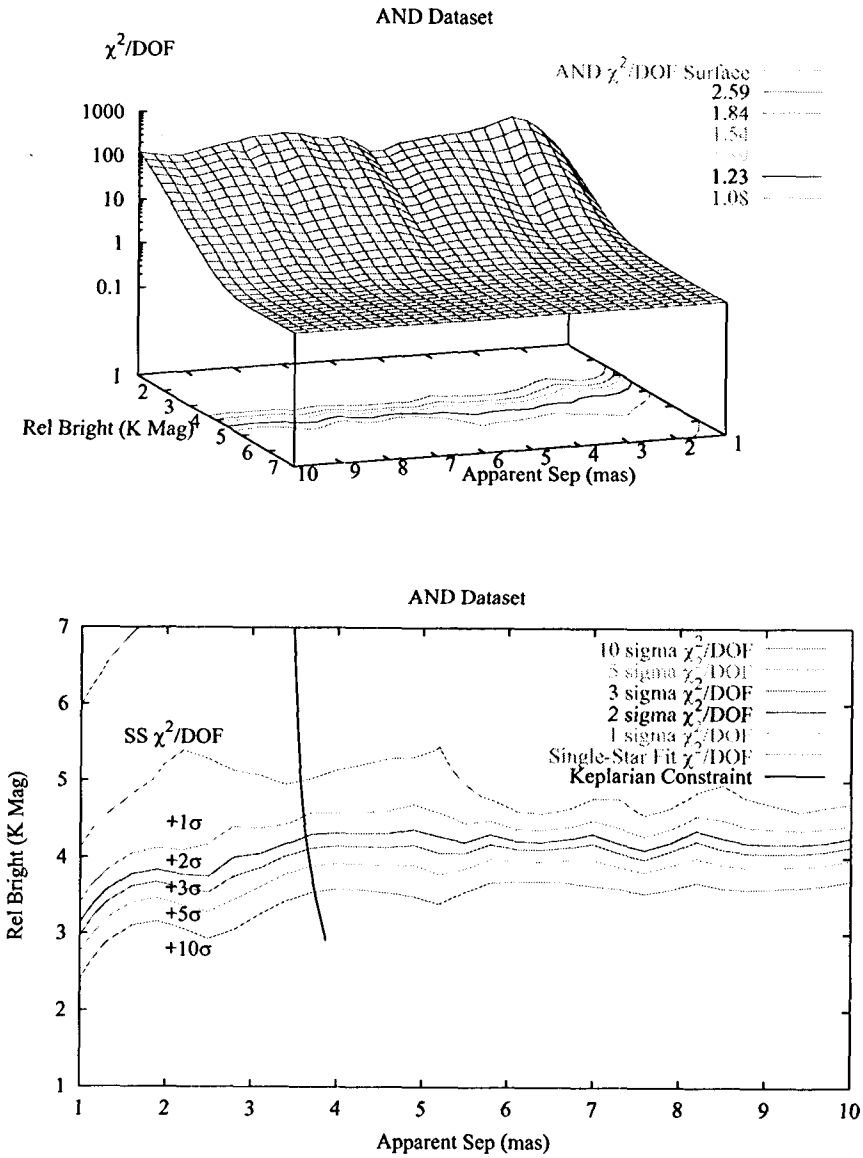

Fig. 3.— AND Dataset Fit to a Binary-Star Hypothesis. a (Top Pannel): the surface of fit χ^2/DOF for our AND dataset to a binary star model for 51 Peg in the space of companion separation (in mas) and relative K-magnitude, along with contours for the single-star hypothesis, and +1, 2, 3, 5, and 10 standard deviations in χ^2/DOF significance. There is no minima in this space of companion parameters that is significantly better than the single-star hypothesis. b (Bottom Pannel): The contour map for the χ^2/DOF surface, and a Keplerian constraint line for a main-sequence companion. A Keplerian companion brighter than 4.53, 4.27, and 4.10 relative K-magnitudes to the 51 Peg primary is excluded at 68%, 95%, and 99% confidence levels respectively.

contours of χ^2/DOF significance, and a constraint curve indicating a Keplerian combination of separation and relative K-magnitude assuming a 1 $M_\odot$ 51 Peg and a main-sequence M-dwarf mass/luminosity relation given by Henry and McCarthy (1993). The Keplerian curve intersects the 1, 2, and 3-sigma χ^2/DOF contours at 4.53, 4.27, and 4.10 relative K-magnitudes. Assuming Gaussian errors in our data and compared with a M_K for 51 Peg of 3.03 (Campins, Rieke, & Lebofsky 1985, Perryman et al 1996), a 4.2-day period Keplerian companion brighter than M_K of 7.56, 7.30, and 7.13 is excluded at 68%, 95%, and 99% confidence levels respectively by this dataset. This same analysis conducted on the OR dataset yields slightly more stringent results (Table 3).

6. Summary

We find no evidence to suggest that the putative 4.2-day period companion to 51 Peg is detectable in our data; all of the datasets we have analyzed indicate that 51 Peg is at least as stable as our two calibration sources. The 1997 PTI data on 51 Peg is sufficiently stable that we can place significant limits on ΔK and consequently M_K of a 4.2-day period companion. We find upper limits in ΔK of 4.78, 4.53, and 4.27 for the 4.2-day period companion to 51 Peg at 68%, 95%, and 99% confidence levels respectively. These ΔK limits imply companion M_K limits of 7.81, 7.56, and 7.30, corresponding to upper limits on the mass of a putative main sequence companion at 0.17, 0.20, and 0.22 $M_\odot$ at the 68%, 95%, and 99% confidence levels respectively (Henry & McCarthy 1993). Our results cannot exclude the possibility of a very low-mass star in a face-on orbit as the 51 Peg companion, but such a star would have to be of spectral type M5V or later.

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	χ^2 Per DOF	Mean Absolute V^2 Residual	Fit Angular Diameter (mas)	# Scans	Calibrators
51 Peg AND	1.08	0.030	0.73 ± 0.02	105	HD 215510, HD 211006
51 Peg OR	1.03	0.028	0.73 ± 0.02	146	HD 215510, HD 211006
HD 215510 Ref 1	1.00	0.030	0.86 ± 0.02	80	HD 211006 @ 1.08 mas
HD 215510 Ref 2	0.65	0.027	0.85 ± 0.02	108	51 Peg @ 0.72 mas
HD 211006 Ref 1	0.73	0.028	1.08 ± 0.02	70	HD 215510 @ 0.85 mas
HD 211006 Ref 2	0.54	0.027	1.08 ± 0.02	72	51 Peg @ 0.72 mas

Table 2: Summary of Single-Star Hypothesis Fitting. This table lists our results on fitting single-star hypotheses to the 51 Peg and calibrator datasets discussed in the text. We see no evidence to suggest an inconsistency of our data with a single-star hypothesis; 51 Peg appears as constant as our two calibration sources. In particular, the resulting fit diameter for 51 Peg essentially reproduces the adopted value used to set the apparent calibrator diameters.

	Single Star χ^2/DOF	Companion M_K Limit		
		$+1\,\sigma$ 68% CL	$+2\,\sigma$ 95% CL	$+3\,\sigma$ 99% CL
51 Peg AND	1.08	7.56	7.30	7.13
51 Peg OR	1.03	7.81	7.56	7.30

Table 3: Summary of Binary-Star Hypothesis Fitting. The table gives absolute K-magnitude lower limits for the putative 4.2-day 51 Peg companion at nominal 1, 2, and 3 sigma significance levels, and nominal 68%, 95%, and 99% confidence levels under the presumption of Gaussian errors in our data. (These are to be compared with an M_K of 3.03 for 51 Peg.) The results from all the datasets are in good agreement, and exclude the possibility of an M-dwarf star earlier than M5V as the putative 4.2-day period companion to 51 Peg.

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