

AN INTERFEROMETRIC SEARCH FOR BRIGHT COMPANIONS TO 51 PEGASI

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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 we 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, which in turn implies a main-sequence companion mass of 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 & Queloz result was quickly verified by several groups with similar or higher resolution spectroscopic techniques (see 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 G5 V spectral classification has become mildly controversial (e.g., Houk 1995 argues for G2-3 V), 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 semimajor axis of approximately 0.05 AU (Marcy et al. 1997)—slightly more if the companion were more massive. At a distance of 15.4 ± 0.2 pc (Perryman et al. 1996), the approximate maximum primary-companion angular separation would be 3.5 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 that 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 110 m 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, which makes a (sufficiently) luminous companion readily detectable.

2. EXPERIMENTAL 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 nonexistent), 51 Peg itself would appear as a single star, exhibiting visibility modulus (and trivially, visibility squared) given in a uniform disk model by

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

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

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

where V_1 and V_2 are the visibility moduli for 51 Peg and the putative companion alone as given by equation (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 of 51 Peg in PTI data is to reliably determine the stability of the V^2 measured on 51 Peg. Without a luminous companion, equation (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 equation (2) predicts sinusoidal excursions in V^2 as the system evolves and the Earth rotates; a companion that is 3 mag fainter 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

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TABLE 1

1997 PTI 51 PEG CALIBRATION OBJECTS CONSIDERED IN OUR ANALYSIS

| Object Name | Spectral Type | Star Mag | 51 Peg Separation | Diameter with Respect to Model 51 Peg |
|-----------------|---------------|--------------|-------------------|---------------------------------------|
| HD 215510 | G6 III | 6.3 V, 3.9 K | 3 $^{\circ}$ 1 | 0.85 \pm 0.06 |
| HD 211006 | K2 III | 5.9 V, 3.4 K | 13 $^{\circ}$ | 1.08 \pm 0.05 |

NOTE.—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).

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, which makes 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 intercomparison. 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 1997 July 19 through November 23. 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, which have a K -band brightness similar (3.96) to 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 the model diameter of 0.72 ± 0.06 mas implied by $R_{51\text{Peg}} = 1.2 \pm 0.1 R_{\odot}$ (adopted by Marcy et al. 1997) and the 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 it leaves open the question of 51 Peg's apparent diameter.

Raw V^2 measurements were made through the methods described in Colavita et al. (1998). An example 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 DATA SETS

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

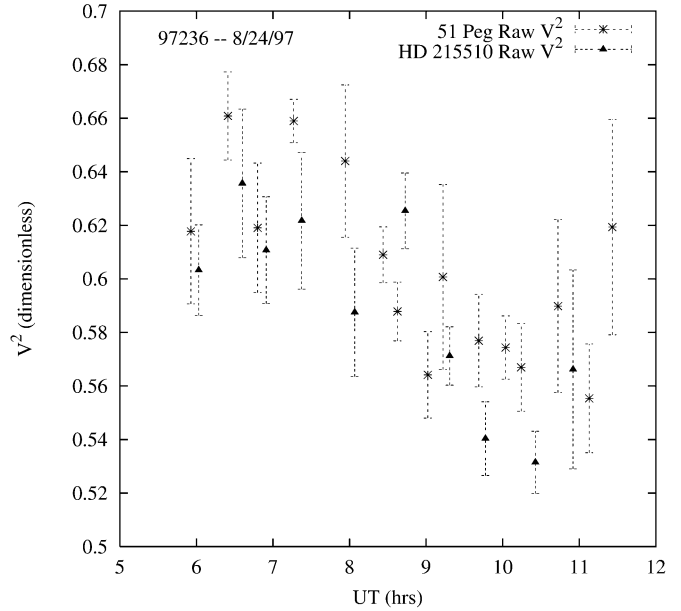


FIG. 1.—Raw V^2 data from a particular night (97236 = 8/24/97) for 51 Peg and a nearby calibrator (HD 215510, 3 $^{\circ}$ 1 away). The V^2 data has been averaged over the 120 s observations, and the sample standard deviation about the mean in each observation is indicated by the error bars. Both 51 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 timescales of approximately 1 hr; we have structured our calibration procedures accordingly.

epoch. In this Letter, we consider 51 Peg data sets calibrated by the two nearby calibration objects (Table 1). We have prepared two different calibrated 51 Peg data sets:

AND Data Set.—This data set requires at least one observation (“scan”) on both nearby calibrators within a ± 1 hr calibration time window (all calibration measurements within the time window are averaged together). This data set contains 105 calibrated scans on 51 Peg over 13 nights spanning a total time interval of 123 days.

OR Data Set.—This data set requires at least one scan on either of the nearby calibrators within the ± 1 hr calibration time window as above. This data set contains 146 scans over 18 nights spanning the same time interval of 123 days. As defined, the AND data set is a proper subset of the OR data set.

4.1 Calibrator Stability

Further, since 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 data sets for each calibration object: (1) calibrated with respect to the other calibration object (i.e., HD 215510 calibrated with respect to HD 211006 and vice versa) and (2) 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 DATA SETS

We have analyzed the calibrated visibility data sets on 51 Peg and the calibrators themselves by fitting single-star (eq. [1]) and double-star (eq. [2]) hypotheses to the data sets and

TABLE 2
SUMMARY OF SINGLE-STAR HYPOTHESIS FITTING

| Data Set or Star | χ^2/dof | Mean Absolute Residual V^2 | Fit Angular Diameter (mas) | Number of 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: | | | | | |
| Reference 1 | 1.00 | 0.030 | 0.86 ± 0.02 | 80 | HD 211006 at 1.08 mas |
| Reference 2 | 0.65 | 0.027 | 0.85 ± 0.02 | 108 | 51 Peg at 0.72 mas |
| HD 211006: | | | | | |
| Reference 1 | 0.73 | 0.028 | 1.08 ± 0.02 | 70 | HD 215510 at 0.85 mas |
| Reference 2 | 0.54 | 0.027 | 1.08 ± 0.02 | 72 | 51 Peg at 0.72 mas |

NOTE.—Results on fitting single-star hypotheses to the 51 Peg and calibrator data sets 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.

by evaluating these hypotheses by considering goodness-of-fit (χ^2) metrics.

5.1 Single-Star Hypothesis

Since a planetary-mass companion to 51 Peg would be too dim to observe with the PTI, it is appropriate to fit a single-star hypothesis to the calibrated data sets for 51 Peg. To accomplish this task, we have used a global nonlinear least-squares fitting code that fits a single-star hypothesis as given in equation (1) to the input-calibrated V^2 data sets on 51 Peg. The single-star hypothesis fits to our data sets are summarized in Table 2.

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. Further, we 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 surprising; 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), with the absolute deviations seen in the calibrator data (see below), and is 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 intercomparisons and fits to calibrator data sets 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 in a statistical (χ^2) sense. In particular, the results in the data sets in which one calibrator is calibrating the other are consistent with the values obtained in the 51 Peg data sets. The data sets 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, so 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, intercomparison 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 than either of the calibrators, both in absolute and in statistical terms.

5.2 Binary Star 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 in which we fit a binary orbit to the V^2 data sets, 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 semimajor 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 semimajor 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 M3 V spectral type at the *Hipparcos* parallax distance, respectively. We used this procedure to map the χ^2 surface in the subspace of the semimajor axis and the intensity ratio.

Figure 2 shows the result of such a fitting procedure applied to the AND data set. This figure depicts a contour map of the χ^2/dof surface over values of the semimajor axis between 0.01 and 0.16 AU (projected separations between 1 and 10 mas) and intensity ratios between 1 and 7 (K magnitudes). At 7 mag difference, we are effectively testing the single-star hypothesis against the data set, 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 and indicates that there is no pattern in the data that 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 the hypothetical semimajor axis.

With 105 degrees of freedom, 1 σ excursions in the χ^2/dof

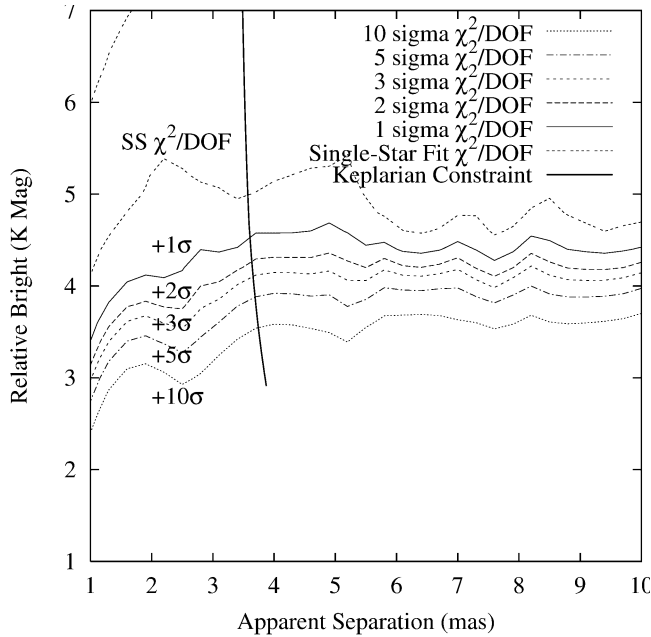


FIG. 2.—AND data set fit to a binary-star hypothesis. Contour map of the surface of fit χ^2/dof for our AND data set to a binary star model for 51 Peg in the space of companion separation (in mas) and relative K magnitude. χ^2/dof contours are given for the single-star hypothesis χ^2/dof , and +1, 2, 3, 5, and 10 σ in χ^2/dof significance. There is no minima in this space of companion parameters that is significantly better than the single-star hypothesis. Superimposed is 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.

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. The contour map gives contours at the single-star fit χ^2/dof , (scaled) 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 & McCarthy (1993). The Keplerian curve intersects the 1, 2, and 3 σ χ^2/dof contours at 4.53, 4.27, and 4.10 relative K magnitudes. Assuming Gaussian

TABLE 3

| DATA SET | SINGLE STAR χ^2/dof | COMPANION M_K LIMIT | | |
|------------------|------------------------------------|-------------------------|-------------------------|-------------------------|
| | | +1 σ (68% CL) | +2 σ (95% CL) | +3 σ (99% CL) |
| 51 Peg AND | 1.08 | 7.56 | 7.30 | 7.13 |
| 51 Peg OR | 1.03 | 7.81 | 7.56 | 7.30 |

NOTE.—The table gives absolute K -magnitude lower limits for the putative 4.2-day 51 Peg companion at nominal 1, 2, and 3 σ 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 data sets are in good agreement and exclude the possibility of an M-dwarf star earlier than M5 V as the putative 4.2 day period companion to 51 Peg.

errors in our data and compared with a M_K for 51 Peg of 3.03 (Campins et al. 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 data set. This same analysis conducted on the OR data set 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 data sets that 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, which correspond 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 M5 V or later.

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