DETECTION LIMITS FROM THE McDONALD OBSERVATORY PLANET SEARCH PROGRAM

ROBERT A. WITTENMYER, MICHAEL ENDL, AND WILLIAM D. COCHRAN
McDonald Observatory, University of Texas at Austin, Austin, TX 78712; robw@astro.as.utexas.edu, mike@astro.as.utexas.edu, wdc@shiraz.as.utexas.edu

ARTIE P. HATZES
Thüringer Landessternwarte Tautenburg, Sternwarte 5, 07778 Tautenburg, Germany

G. A. H. WALKER AND S. L. S. YANG
Department of Physics and Astronomy, University of Victoria, Victoria, BC V8W 3P6, Canada

AND

DIANE B. PAULSON
NASA Goddard Space Flight Center, Code 693, Planetary Systems Branch, Greenbelt, MD 20771

Received 2006 February 9; accepted 2006 April 7

ABSTRACT

Based on the long-term radial velocity surveys carried out with the McDonald Observatory 2.7 m Harlan J. Smith Telescope from 1988 to the present, we derive upper limits to long-period giant planet companions for 31 nearby stars. Data from three phases of the McDonald Observatory 2.7 m planet-search program have been merged together, and for 17 objects data from the pioneering Canada-France-Hawaii Telescope radial velocity program have also been included in the companion-limits determination. For those 17 objects, the baseline of observations is in excess of 23 yr, enabling the detection or exclusion of giant planets in orbits beyond 8 AU. We also consider the possibility of eccentric orbits in our computations. At an orbital separation of 5.2 AU, we can exclude on average planets of $M \sin i > (2.0 \pm 1.1) M_J (e = 0)$ and $M \sin i > (4.0 \pm 2.8) M_J (e = 0.6)$ for 25 of the 31 stars in this survey. However, we are not yet able to rule out “true Jupiters,” i.e., planets of $M \sin i \sim 1 M_J$ in 5.2 AU orbits. These limits are of interest for the *Space Interferometry Mission*, *Terrestrial Planet Finder*, and *Darwin* missions, which will search for terrestrial planets orbiting nearby stars, many of which are included in this work.

Key words: planetary systems — techniques: radial velocities

Online material: planetary systems — techniques: radial velocities

1. INTRODUCTION

In the 10 years since the discovery of the first extrasolar planet orbiting a main-sequence star (Mayor & Queloz 1995) more than 170 planets have been discovered. The vast majority of these have been detected via high-precision radial velocity measurements of the planet’s gravitational influence on its host star. Current Doppler surveys now routinely achieve precisions of 2–3 m s$^{-1}$ (e.g., Cochran et al. 2004), facilitating the detection of ever-lower mass companions, such as the “hot Neptunes” (Bonfils et al. 2005; McArthur et al. 2004; Santos et al. 2004b; Butler et al. 2004) and even “super-Earths” (Rivera et al. 2005).

However, there exists a relatively long record of radial velocity data at somewhat lower precision (~15–20 m s$^{-1}$) that ought not to be ignored. Such data now cover nearly a quarter century (Campbell & Walker 1979; Campbell et al. 1988; Walker et al. 1995), and as such are extremely useful in probing nearby stars for long-period giant planets akin to our own Jupiter (orbital period 11.9 yr). These data sets are valuable tools in the search for extrasolar analogs to our solar system. We are now beginning to obtain meaningful answers to some of the following questions: What is the frequency of long-period giant planets in the solar neighborhood? What implications would the lack of such planets have on theories of planet formation? How many planetary systems resemble our own solar system?

In this work we merge radial velocity data from three phases of observations at the McDonald Observatory, and we also include data from the Canada-France-Hawaii Telescope (CFHT) study of Walker et al. (1995). In § 2 we describe the data sets, in § 3 we describe the merging procedure and outline the algorithm used to derive companion limits, and in § 4 we present and discuss the constraints these data place on the presence of planets orbiting these stars.

2. OBSERVATIONS

2.1. A Brief History of Radial Velocity Planet Detection

Radial velocity searches for planets around other stars began well before the 1995 discovery of 51 Peg b. Griffin & Griffin (1973) showed that the fundamental limit to the precision of classical radial velocity techniques was not the instruments used but rather was a result of the calibration processes. They pointed out that the optical paths followed by the stellar beam and the separate comparison source illuminated the spectrograph optics differently. Tull (1969) demonstrated how zonal errors in spectrograph optics contribute directly to wavelength (and thus velocity) errors. In addition, thermal and mechanical motion of the spectrograph in the time interval between obtaining the stellar and calibration observations also contributed to the measured velocity errors. Griffin & Griffin (1973) proposed that these sources of errors could be defeated through the calibration of the spectrograph by an absorption-line spectrum imposed on the stellar light before it entered the spectrograph. They suggested that the use of the very convenient absorptions by the Earth’s atmospheric O$_2$ band at 6300 Å would permit stellar radial velocities to be measured to a precision perhaps as good as 0.01 km s$^{-1}$. Campbell & Walker (1979) first used an externally applied absorption spectrum to provide a stable velocity metric for precise radial velocity
measurement as applied to planet detection. Instead of the telluric absorption spectrum, they chose to use a stabilized HF gas absorption cell in front of the coudé spectrograph of the CFHT. The HF 3–0 R branch lines near 8700 Å were used as applied to planet detection. Instead of the telluric I$_2$ B3 $\gamma$ band as a velocity reference system, in application to his measurements of the solar rotation. Koch & Woehl (1984) then extended this use of the B–X I$_2$ band to the measurement of the Doppler shifts of several solar photospheric absorption lines. Libbrecht (1988) then extended the use of I$_2$ as a velocity metric in searching for p-mode oscillations of α CMi. Marcy & Butler (1992) then implemented the use of the I$_2$ velocity metric for large-scale precise radial velocity surveys for extrasolar planets. The use of an I$_2$ cell offers the major advantage that the I$_2$ lines can be used to measure the spectrometer instrumental profile (Valenti et al. 1995) and thus measure very precise radial velocity variations (Butler et al. 1996). An alternative is to use an optical-fiber-fed cross-dispersed echelle spectrograph with simultaneous wavelength calibration. This was first done with ELODIE (Baranne et al. 1996) and later with CORALIE (Queloz et al. 2000). To further improve precision with this technique, the HARPS instrument (Rupprecht et al. 2004) is placed in a temperature-stabilized vacuum chamber.

2.2. The McDonald Observatory Planetary Search Program

The McDonald Observatory Planetary Search program comprises a large, multifaceted investigation to detect and characterize planetary companions to other stars in our galaxy. It began in 1988 as a high-precision radial velocity survey of bright nearby stars using the McDonald Observatory 2.7 m Harlan J. Smith Telescope and coudé spectrograph, but has expanded substantially in size and scope since then. Phase I of the radial velocity planet search program used the telluric O$_2$ lines near 6300 Å as the velocity metric, a technique suggested by Griffin & Griffin (1973).

| Star       | HR   | Spectral Type | $V$ Magnitude | Mass (M$_\odot$) | Reference for Mass Estimate |
|------------|------|---------------|---------------|------------------|-----------------------------|
| η Cas      | 219  | G0 V          | 3.44          | 0.90             | Allende Prieto & Lambert (1999) |
| τ Cet      | 509  | G8 V          | 3.50          | 0.65             | Santos et al. (2004a) |
| θ Per      | 799  | F8 V          | 4.12          | 1.15             | Allende Prieto & Lambert (1999) |
| ι For      | 937  | G0 V          | 4.04          | 1.23             | Allende Prieto & Lambert (1999) |
| κ Cet      | 121  | F8 V          | 3.87          | 1.30             | Allende Prieto & Lambert (1999) |
| δ Eri      | 1136 | K0 IV         | 3.54          | 0.96             | Allende Prieto & Lambert (1999) |
| ζ Eri      | 1325 | K1 V          | 4.43          | 0.65             | Santos et al. (2004a) |
| π $^3$ Ori | 1543 | F6 V          | 3.19          | 1.24             | Allende Prieto & Lambert (1999) |
| λ Aur      | 1729 | G1.5 IV–V     | 4.71          | 1.15             | Allende Prieto & Lambert (1999) |
| θ Uma      | 3775 | F6 IV         | 3.17          | 1.53             | Allende Prieto & Lambert (1999) |
| 36 UMa     | 4112 | F8 V          | 4.82          | 1.14             | Allende Prieto & Lambert (1999) |
| β Vir      | 4540 | F8 V          | 3.61          | 1.36             | Allende Prieto & Lambert (1999) |
| β Com      | 4983 | G0 V          | 4.28          | 1.05             | Allende Prieto & Lambert (1999) |
| 61 Vir      | 5019 | G6 V          | 4.75          | 1.01             | Allende Prieto & Lambert (1999) |
| ζ Boo A    | 5544 | G8 V          | 4.55          | 0.86             | Fernandes et al. (1998) |
| λ Ser      | 5868 | G0 V          | 4.43          | 0.97             | Allende Prieto & Lambert (1999) |
| γ Ser      | 5933 | F6 V          | 3.85          | 1.28             | Allende Prieto & Lambert (1999) |
| 36 Oph A   | 6402 | K1 V          | 5.29          | 0.78             | Walker et al. (1995) |
| μ Her      | 6623 | G5 IV         | 3.42          | 1.10             | do Nascimento et al. (2003) |
| 70 Oph A   | 6752 | K0 V          | 4.03          | 0.97             | Allende Prieto & Lambert (1999) |
| σ Dra      | 7462 | K0 V          | 4.68          | 0.85             | Nelson & Angel (1998) |
| 16 Cyg A   | 7503 | G1.5 V        | 5.96          | 0.98             | Allende Prieto & Lambert (1999) |
| 31 Aql     | 7373 | G8 IV         | 5.16          | 0.95             | do Nascimento et al. (2003) |
| β Aql      | 7602 | G8 IV         | 3.71          | 1.50             | do Nascimento et al. (2003) |
| γ Del      | 7948 | K1 IV         | 4.27          | 1.90             | do Nascimento et al. (2003) |
| η Cep      | 7957 | K0 IV         | 3.43          | 1.39             | Allende Prieto & Lambert (1999) |
| 61 Cyg A   | 8085 | K5 V          | 5.21          | 0.67             | Walker et al. (1995) |
| 61 Cyg B   | 8086 | K7 V          | 6.03          | 0.59             | Walker et al. (1995) |
| HR 8832    | 8832 | K3 V          | 5.56          | 0.79             | Nelson & Angel (1998) |
| ι Psc      | 8969 | F7 V          | 4.13          | 1.38             | Allende Prieto & Lambert (1999) |
A single order of the McDonald 2.7 m telescope coude echelle spectrograph (cs12) was isolated onto a Texas Instruments 800 × 800 CCD at R = 210,000. This system gave about 20 m s\(^{-1}\) precision on stars down to \(V = 6\) but suffered from systematic velocity errors, possibly due to prevailing atmospheric winds. Diurnal and seasonal variability in the winds introduced spurious periodic signals in the data. We therefore switched to a temperature-stabilized \(I_2\) cell as the velocity metric in 1992. This eliminated the systematic errors and gave a routine radial velocity precision of \(\sim 15\) m s\(^{-1}\). This precision was limited by

### TABLE 2: SUMMARY OF OBSERVATIONS

| Star      | \(N\) | \(T\) (yr) | CFHT rms (m s\(^{-1}\)) | Phase I rms (m s\(^{-1}\)) | Phase II rms (m s\(^{-1}\)) | Phase III rms (m s\(^{-1}\)) | \(\log R'_{\text{HK}}\) |
|-----------|-------|------------|--------------------------|-----------------------------|-----------------------------|-----------------------------|---------------------------|
| \(\eta\) Cas | 131   | 16.3       | ...                      | 28.1                        | 28.9                        | 7.3                         | -4.926                    |
| \(\tau\) Cet | 183   | 23.3       | 14.2                     | 22.3                        | 28.7                        | 10.4                        | -4.979                    |
| \(\theta\) Per | 65    | 9.5        | ...                      | 59.6                        | 17.9                        | -4.919                      |
| \(i\) Per   | 165   | 23.9       | 18.2                     | 30.0                        | 18.6                        | 10.2                        | -5.041                    |
| \(\alpha\) For | 66    | 15.3       | ...                      | 28.9                        | 41.3                        | 15.8                        | -5.023                    |
| \(\kappa^3\) Cet | 134   | 23.0       | 23.7                     | 34.4                        | 29.7                        | 20.1                        | -4.441                    |
| \(\delta\) Eri | 109   | 16.1       | ...                      | 17.8                        | 22.5                        | 9.4                         | -5.228                    |
| \(\sigma^2\) Eri | 138   | 22.1       | 18.6                     | 30.4                        | 18.0                        | 14.6                        | -4.951                    |
| \(\pi^3\) Ori | 160   | 15.9       | ...                      | 169.9                       | 113.3                       | 26.4                        | -4.716                    |
| \(\lambda\) Aur | 63    | 10.4       | ...                      | ...                         | ...                         | ...                         | ...                       |
| \(\theta\) UMa | 268   | 18.3       | 18.8                     | 43.1                        | 43.7                        | 14.8                        | -5.608                    |
| \(36\) UMa | 194   | 23.0       | 21.0                     | 19.4                        | 22.4                        | 8.2                         | -4.811                    |
| \(\beta\) Vir | 205   | 23.3       | 28.4                     | 30.5                        | 32.6                        | 7.6                         | -4.942                    |
| \(\beta\) Com | 191   | 22.4       | 18.4                     | 31.7                        | 42.0                        | 11.1                        | -4.749                    |
| \(61\) Vir | 149   | 23.0       | 18.4                     | 25.8                        | 31.0                        | 7.8                         | -5.030                    |
| \(\xi\) Boo A | 186   | 23.3       | 23.6                     | 34.5                        | 31.9                        | 23.3                        | -4.420                    |
| \(\lambda\) Ser | 63    | 11.5       | ...                      | ...                         | ...                         | ...                         | ...                       |
| \(\gamma\) Ser | 149   | 15.1       | ...                      | 84.7                        | 41.6                        | 25.6                        | -4.934                    |
| \(36\) Oph A | 91    | 21.9       | 20.1                     | 21.5                        | 33.1                        | 16.3                        | -4.614                    |
| \(\mu\) Her | 173   | 16.9       | ...                      | 28.4                        | 24.4                        | 9.2                         | -5.092                    |
| \(70\) Oph A | 98    | 16.2       | ...                      | 111.4                       | 43.3                        | 17.4                        | -4.736                    |
| \(\sigma\) Dra | 178   | 23.6       | 14.5                     | 21.5                        | 23.1                        | 9.9                         | -4.865                    |
| \(16\) Cyg A | 102   | 16.0       | ...                      | 34.4                        | 29.0                        | 6.9                         | -5.018                    |
| \(31\) Aql | 38    | 7.9        | ...                      | ...                         | ...                         | ...                         | ...                       |
| \(\beta\) Aql | 183   | 22.1       | 14.6                     | 28.0                        | 20.1                        | 16.4                        | -5.171                    |
| \(\gamma^2\) Del | 103   | 15.0       | ...                      | 23.7                        | 21.7                        | 16.8                        | -5.354                    |
| \(\eta\) Cep | 187   | 23.5       | 19.2                     | 29.5                        | 16.4                        | 9.6                         | -5.223                    |
| \(61\) Cyg A | 143   | 23.4       | 20.7                     | 22.3                        | 13.5                        | 7.2                         | -4.862                    |
| \(61\) Cyg B | 121   | 22.4       | 16.9                     | 23.5                        | 16.2                        | 3.9                         | -4.962                    |
| HR 8832 | 119   | 22.9       | 14.9                     | 22.8                        | 13.8                        | 12.9                        | -5.013                    |
| \(\omega\) Pac | 54    | 11.2       | ...                      | ...                         | ...                         | ...                         | ...                       |

\[Fig. 1.—\text{Quadratic fits to } \mu\text{ Her data (left) and } \xi\text{ Boo A (right). [See the electronic edition of the Journal for a color version of this figure.]}\]
the 9.6 Å bandpass of the single order of the echelle grating and by the poor charge-transfer and readout properties of the TI
800 × 800 CCD. To solve these problems and to achieve substantially improved precision, we began Phase III of the radial
velocity program in 1998 July, using the same I_2 cell with the newly installed 2dcoudé cross-dispersed echelle spectrograph
(Tull et al. 1994) with its 2048 × 2048 Tektronix CCD. We set
up the spectrograph to include echelle orders from 3594 to
10762 Å, which covers the Ca ii H and K lines used to measure
stellar activity. Wavelength coverage is complete from the blue
end to 5691 Å, and there are increasingly large interorder gaps
from there to the red end (Tull et al. 1995). Using the full 1200 Å
bandpass of the I_2 absorption band at the
R = 60,000 focus of the 2dcoudé allows routine internal precision of 6–9 m s^{-1} to be achieved. The McDonald program has subsequently been expanded significantly to include a collaboration with M. Kürster and colleagues on southern hemisphere radial velocity surveys using the facilities of ESO at La Silla and the Very Large Telescope (VLT; Kürster et al. 2000, 2003; Endl et al. 2002), a program to use the Keck 1 HIREs spectrograph to search for planetary companions to stars in the Hyades (Cochran et al. 2002; Paulson et al. 2002, 2003a, 2004b), and use of the High Resolution Spectrograph on the Hobby-Eberly Telescope (Cochran et al. 2004). Observations from the McDonald planet search program have been used in the discovery of four planets: 16 Cyg Bb (Cochran et al. 1997), γ Cep Ab (Hatzes et al. 2003), ε Eri b (Hatzes et al. 2000), and HD 13189b (Hatzes et al. 2003).

| Parameter | Estimate | Uncertainty |
|-----------|----------|-------------|
| Period (yr) | 179.1 | 99.5 |
| T_0 (HJD) | 24454610.22 | 91.74 |
| e | 0.69 | 0.11 |
| ω (deg) | 193.6 | . . |
| K_2 (m s^{-1}) | 4163 | 257 |

**Table 3**

| Star | Period (days) | FAP |
|------|---------------|-----|
| η Cas | 2.964 | 0.296 |
| τ Cet | 8.389 | 0.034 |
| θ Per | 348.422 | 0.443 |
| α Per | 91.996 | 0.027 |
| α For | 8.262 | 0.395 |
| κ^1 Cet | 33.069 | 0.034 |
| δ Eri | 22.051 | 0.788 |
| α^2 Eri | 7.463 | 0.900 |
| π^3 Ori | 73.260 | 0.008 |
| λ Aur | 2.549 | 0.188 |
| θ Uma | 2.587 | 0.178 |
| 36UMa | 3703.704 | 0.694 |
| β Vir | 3.307 | 0.262 |
| β Com | 9.946 | 0.315 |
| 61 Vir | 9.777 | 0.072 |
| ζ Boo A | 6.298 | 0.202 |
| κ Ser | 4.929 | 0.773 |
| γ Ser | 8.961 | 0.137 |
| 36 Oph A | 2.641 | 0.565 |
| μ Her | 7.623 | 0.039 |
| 70 Oph A | 6.138 | 0.989 |
| σ Dra | 30.553 | 0.109 |
| 16 Cyg A | 2.873 | 0.038 |
| 31 Aql | 8.374 | 0.536 |
| β Aql | 2.800 | 0.019 |
| γ^2 Del | 3.837 | 0.099 |
| η Cep | 5.940 | 0.030 |
| 61 Cyg A | 6.570 | 0.159 |
| 61 Cyg B | 6.872 | 0.846 |
| HR 8832 | 25.227 | 0.144 |
| i Psc | 2.499 | 0.144 |

**Table 4**

![Fig. 2. — Orbital solution for the visual binary 70 Oph A using data from Batten et al. (1984) (filled circles) and McDonald Observatory Phases I–III (open circles). [See the electronic edition of the Journal for a color version of this figure.]](image1)

![Fig. 3. — Effect of eccentricity on limit determinations. Allowing higher eccentricities reduces the sensitivity somewhat, due to the increased probability of unfortunately phased observations. [See the electronic edition of the Journal for a color version of this figure.]](image2)
2005). McDonald data were also instrumental in the detection of the brown dwarf HD 137510b (Endl et al. 2004).

2.3. Observational Data Presented Here

The majority of the data used in this study were obtained by the McDonald Observatory program Phases I–III using the 2.7 m Harlan J. Smith telescope. A list of the target stars is given in Table 1. For 17 of the 31 stars in this study, additional data were available from the CFHT precision radial velocity work of Walker et al. (1995). Table 2 gives a summary of all four data sets, including the total time span, rms of each data set, and the chromospheric emission ratio log \( R_{HK} \) (Noyes et al. 1984) computed from the McDonald Phase III measurements of the Ca \( \Pi \) S-index. The rms values listed in Table 2 include the internal uncertainties of 6–9 \( \text{m s}^{-1} \) and the velocity jitter inherent to each star.

3. DATA ANALYSIS

3.1. Merging the Data

Since each of the four data sets consists of velocities measured relative to an independent and arbitrary zero point, it was necessary to implement a consistent and robust method of combining them. Before merging, an iterative outlier-rejection routine was applied to each data set separately. Data points that were more than 3.3 times the rms from the mean were rejected. This criterion corresponds to a 99.9% confidence level for a Gaussian distribution. The mean and rms were then recomputed, and the outlier rejection was repeated until no more points were rejected. As the targets are well-studied constant-velocity stars, we are confident that we have a well-defined distribution about the mean. For the visual binary 70 Oph A, several velocities were systematically too low due to spectral contamination caused by the chance alignment of both components on the slit, and these points were also removed. The fainter component (\( \Delta m = 1.8 \text{ mag} \)) adds a Doppler-shifted second spectrum, which distorts the line shapes. Since our velocity computation method assumes a single set of lines, the resulting velocity is skewed by this contamination.

The merging of these data sets was accomplished in the following manner: McDonald Phases II and III were joined with a trial offset, and a least-squares linear fit of a trend of velocity with time was performed on the combination. The offset between the Phase II and III data sets that minimizes the rms about that linear fit is the one that is applied in order to merge the two phases together. This process was then repeated sequentially to join the Phase I and then the CFHT data to the growing data string. The least-squares fitting allows for a linear trend to be present; the merging process was redone for all nonbinaries, this time forcing the slope to be zero (i.e., minimizing the rms about the mean of the combined data for a grid of trial offsets). The rms about the mean of data merged in this manner was compared to the rms about a linear fit to data merged allowing a trend. Since our null hypothesis is that the stars have constant radial velocity, the method that allowed a slope was only chosen for the nine stars that showed an improvement in the rms of the merged data set when a slope was allowed. Those stars were \( \eta \) Cep, \( \eta \) Cas, \( \alpha \) For, \( \theta \) UMa, \( \xi \) Boo A, \( \mu \) Her, 70 Oph A, and 61 Cyg A and B. All of these stars are well-known long-period binaries, so the use of a slope was justified.

The orbital periods of these nine known binaries were sufficiently long that a simple linear approximation was sufficient, except for \( \mu \) Her, \( \xi \) Boo A (quadratic trend), and 70 Oph A (Keplerian solution). Fits to these trends were subtracted from the data sets, and the residuals were used as input for the detection-limit algorithm. The three data sets on the visual binary \( \mu \) Her...
were merged in a similar manner. The binary period (43.2 yr) is such that a linear trend is a suboptimal approximation for the purposes of merging the 16.9 yr of data, and a quadratic fit was used to approximate the shape of the orbit. This procedure was also used for ξ Boo A; the data and fits are shown in Figure 1. For 70 Oph A, the quadratic approximation was still insufficient, as the 16.1 yr of available data represent a significant portion of the 91.44 yr published orbital period (Batten et al. 1984), and an orbital solution for the binary system had to be obtained using GaussFit (Jefferys et al. 1987). The solution to the combined data set (McDonald Phases I–III plus much lower precision data from Batten et al. 1984) are given in Table 3 and plotted in Figure 2. The large uncertainties in the fitted parameters are due to the fact that the available data do not encompass a complete orbit, and hence the model is poorly constrained. The fitted value of $\omega$ was derived by a rudimentary grid search around the published value, as GaussFit would not converge with $\omega$ as a free parameter. The orbital parameters of the binary system are substantially different than those reported in Batten et al. (1984), likely owing to the fact that the McDonald velocities, which are an order of magnitude more precise, drive the fit. Only the McDonald data were used in the computation of companion limits for 70 Oph A.

3.2. Periodogram Analysis

After the data sets were merged together, and trends due to binary orbits were subtracted, we searched for periodicities using a Lomb-Scargle periodogram (Lomb 1976; Scargle 1982). False alarm probabilities (FAPs) were established using a bootstrap randomization method as described in Küster et al. (1997) and Endl et al. (2002). This bootstrap method, unlike the nominal analytic FAP formula of Scargle (1982), makes no assumptions about the distribution of the data; rather, the error distribution of the actual data themselves is used. The periodogram search interval was from 2 days up to the full extent of observations for each object. We used 10,000 bootstrap randomizations to determine the FAP of the highest peak in the periodogram for each star; the results are given in Table 4. Only one star had a periodicity with a significance greater than 99%: π³ Ori, with a peak at 73.26 days and a bootstrap FAP of 0.8%. As this is an active early-type (F6 V) star, we are confident that this is due to a combination of stellar activity and reduced velocity precision (from the paucity of lines) rather than the presence of a companion. In addition, no peak was evident in a periodogram on the more precise McDonald Phase III data alone, supporting our conclusion that it is a spurious noise spike.

3.3. Determination of Companion Limits

Companion limits were determined via an algorithm that injected test signals into the data, and then attempted to recover these signals using a periodogram search. Test signals were generated using the method of Lehmann-Filhés (1894) as described in Binnendijk (1960):

$$V_r = \gamma + K[e \cos \omega + \cos (\nu + \omega)],$$

where $V_r$ is the radial velocity, $\gamma$ is the systemic velocity, $K$ is the velocity semiamplitude, $e$ is the orbital eccentricity, $\omega$ is the argument of periastron, and $\nu$ is the true anomaly. In the above equation, $\nu$ can be expressed in terms of observables via the following relations:

$$\tan \frac{\nu}{2} = \left(\frac{1 + e}{1 - e}\right)^{1/2} \tan \frac{E}{2},$$

$$M = \frac{2\pi}{P}(t - T_0) = E - e \sin E,$$

where $V_r$ is the radial velocity, $\gamma$ is the systemic velocity, $K$ is the velocity semiamplitude, $e$ is the orbital eccentricity, $\omega$ is the argument of periastron, and $\nu$ is the true anomaly. In the above equation, $\nu$ can be expressed in terms of observables via the following relations:
for a signal with period \( P \), periastron passage time \( T_0 \), observation time \( t \), mean anomaly \( M \), and eccentric anomaly \( E \). For each data set the algorithm stepped through 300 trial periods at even steps in the logarithm between 2 days and the total duration of observations. At each trial period the program sampled 30 phase steps of the periastron time \( T_0 \), and for nonzero eccentricities sampled 36 values of the argument of periastron \( \omega \) at intervals of \( 10/\gamma \). The velocity semiamplitude \( K \) of the test signal was allowed to vary from 10 to 1000 m s\(^{-1}\). The systemic velocity \( \gamma \) of each combined data set was forced to be equal to zero. For each set of Keplerian orbital parameters, synthetic radial velocities were generated using the observation times from the input data. This simulated signal was then added to the data, and a Lomb-Scargle periodogram was used to attempt to recover that signal. For a signal to count as having been recovered, the periodogram’s highest peak had to occur at the correct period with a FAP of less than 0.1%. The FAP was estimated using the formula from Horne & Baliunas (1986). For each \( K \)-value, 99% of the 1080 test signals\(^2\) had to be recovered in this manner in order for that velocity semiamplitude (corresponding to a planet of a given mass at a given semimajor axis) to be considered “ruled out” by the data. If more than 1% of the orbital configurations tested at a given \( K \)-value were not ruled out in this manner, the algorithm increased \( K \) by 1 m s\(^{-1}\) and repeated the process until it was able to recover 99% of the parameter configurations (\( e, \omega, \) and \( T_0 \)) that were tested. Once this occurred, the planetary mass ruled out was computed by the following:

\[
M_2 \sin i = (1 - e^2)^{1/2} \left[ (1.036 \times 10^{-7})M_1^2 PK^3 \right]^{1/3},
\]

where \( M_1 \) is the stellar mass in solar masses, \( P \) is the orbital period in days, \( K \) is the radial velocity semiamplitude in km s\(^{-1}\), and \( M_2 \sin i \) is the projected planetary mass in solar masses. The algorithm then moved to the next trial period and repeated the entire process.

Unlike most previous companion limit determinations (Murdoch et al. 1993; Walker et al. 1995; Nelson & Angel 1998; Cumming et al. 1999; Endl et al. 2002), this procedure allows for nonzero eccentricities in the trial orbits (but see Desidera et al. 2003). For the eccentric case, a value of \( e = 0.6 \) was chosen; of the known extrasolar planets, 90% have \( e < 0.6 \) (Marcy et al. 2005). Allowing higher eccentricities substantially reduced the ability to rule out the test signals, as the sporadic sampling of the data would likely miss the relatively high-velocity points near periastron. Figure 3 shows the effect of allowing various ranges of eccentricity. Note that although the limits derived by this study are rendered somewhat less stringent by the inclusion of nonzero eccentricities, the effect is relatively minor for our adopted value of \( e = 0.6 \). Allowing a larger range of eccentricities (up to \( e = 0.9 \)), however, substantially reduces the sensitivity of the companion-limit determination, as demonstrated in Figure 3. We emphasize that the upper limits derived by the method described above are much more stringent, and hence result in higher companion-mass limits than those reported by previous studies.

4. RESULTS AND DISCUSSION

Limits to planetary companions derived using these data are shown in Figures 4–11. In each panel the lower set of points (solid line) represents the companion limits for the zero-eccentricity case, and the dotted line is for the case of \( e = 0.6 \). Notably, despite the abundance and quality of data available in this study, we are as yet unable to rule out any planets with \( M \sin i \lesssim 1M_J \) in 5.2 AU orbits with eccentricities as large as \( e = 0.6 \).
only circular orbits are considered, such objects can be ruled out
for τ Cet, σ Dra, 61 Cyg A, and 61 Cyg B. Table 5 lists the
minimum planet masses that can be excluded by these data at
selected semimajor axes, for the $e = 0$ and 0.6 cases. The results
given in Table 5 are shown in histogram format in Figure 12,
which indicates that for most stars in this survey, Saturn-mass
planets in close orbits ($a \sim 0.1$ AU) can be ruled out.

It is also useful to consider the effect of giant planets in inter-
mediate orbits ($a \sim 2–3$ AU), which may perturb lower mass
planets within the habitable zone of the star. If such objects can
be excluded with confidence, their host stars become attractive
candidates for the Terrestrial Planet Finder (TPF) and Darwin
missions, which aim to detect Earthlike planets in the habitable
zone. Menou & Tabachnik (2003) defined a planet’s zone of

![Fig. 7.—Same as Fig. 4, but for β Vir, β Com, 61 Vir, and ξ Boo A. [See the electronic edition of the Journal for a color version of this figure.]](image1)

![Fig. 8.—Same as Fig. 4, but for λ Ser, γ Ser, 36 Oph A, and μ Her. [See the electronic edition of the Journal for a color version of this figure.]](image2)
influence to extend from $R_{\text{in}} = (1 - e)a - 3R_{\text{Hill}}$ to $R_{\text{out}} = (1 + e)a + 3R_{\text{Hill}}$, where the Hill radius is

$$R_{\text{Hill}} = a \left( \frac{M_p}{3M_*} \right)^{1/3},$$

(5)

and $e$ is the planet’s eccentricity, $a$ is its semimajor axis, $M_p$ is its mass, and $M_*$ is the mass of the star. Simulations by Menou & Tabachnik (2003) demonstrated that terrestrial planets were nearly always ejected or consumed in systems in which an eccentric giant planet’s zone of influence overlapped the habitable zone. We can then ask whether the companion limits derived in this work can be used to exclude such perturbing bodies. Such a pursuit is limited by the fact that even distant giant planets can disrupt the habitable zone if their orbits are sufficiently eccentric, and as shown in Figure 1, the nature of the radial velocity data is such that...

Fig. 9.—Same as Fig. 4, but for 70 Oph A, σ Dra, 16 Cyg A, and 31 Aql. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 10.—Same as Fig. 4, but for β Aql, γ² Del, η Cep, and 61 Cyg A. [See the electronic edition of the Journal for a color version of this figure.]
### Minimum-Mass Companion Limits

| STAR          | 0.05 AU, $e = 0.0$ | 0.1 AU, $e = 0.0$ | 3 AU, $e = 0.6$ | 3 AU, $e = 0.0$ | 5.2 AU, $e = 0.6$ | 5.2 AU, $e = 0.0$ |
|---------------|--------------------|--------------------|----------------|----------------|--------------------|--------------------|
| η Cas         | 0.13               | 0.17               | 1.30           | 0.87           | 2.31               | 1.37               |
| τ Cet         | 0.09               | 0.16               | 1.14           | 0.67           | 1.34               | 0.90               |
| θ Per         | 0.48               | 0.62               | 5.71           | 3.46           | 2.70               | 1.69               |
| ρ Per         | 0.12               | 0.16               | 1.46           | 0.95           | 3.26               | 2.19               |
| α For         | 0.32               | 0.57               | 6.12           | 3.05           | 8.46               | 4.37               |
| ρ2 Cet        | 0.18               | 0.27               | 2.34           | 1.44           | 3.81               | 2.05               |
| δ Per         | 0.13               | 0.19               | 2.10           | 1.07           | 12.74              | 1.88               |
| ω2 Eri        | 0.12               | 0.16               | 1.33           | 0.88           | 1.66               | 1.16               |
| π1 Ori        | 0.84               | 1.51               | 9.79           | 6.01           | 46.70              | 8.54               |
| λ Aur         | 0.18               | 0.24               | 2.19           | 1.25           | 4.60               | 2.57               |
| θ UMa         | 0.24               | 0.36               | 3.09           | 1.96           | 4.60               | 2.57               |
| 36 UMa        | 0.13               | 0.17               | 1.46           | 0.91           | 2.54               | 1.71               |
| β Vir         | 0.16               | 0.23               | 2.49           | 1.57           | 4.19               | 2.61               |
| β Com         | 0.16               | 0.26               | 1.95           | 1.24           | 3.29               | 2.22               |
| 61 Vir        | 0.14               | 0.20               | 1.62           | 1.16           | 2.58               | 1.69               |
| ξ Boo A       | 0.16               | 0.19               | 2.00           | 1.24           | 2.61               | 1.78               |
| λ Ser         | 0.16               | 0.21               | 2.01           | 1.14           | 2.55               | 1.52               |
| γ Ser         | 0.44               | 0.49               | 4.15           | 2.97           | 10.89              | 5.80               |
| 36 Oph A      | 0.19               | 0.23               | 2.24           | 1.39           | 5.83               | 2.33               |
| μ Her         | 0.14               | 0.21               | 1.53           | 0.96           | 2.55               | 1.52               |
| 70 Oph A      | 0.46               | 0.84               | 8.71           | 5.04           | 12.78              | 7.19               |
| σ Dra         | 0.11               | 0.12               | 1.12           | 0.79           | 1.60               | 1.03               |
| 16 Cyg A      | 0.18               | 0.32               | 2.21           | 1.38           | 5.44               | 2.45               |
| 31 Aql        | 0.22               | 0.38               | 3.37           | 1.90           | 6.54               | 3.33               |
| β Aql         | 0.12               | 0.18               | 1.61           | 1.04           | 2.67               | 1.77               |
| γ2 Del        | 0.22               | 0.32               | 2.55           | 1.60           | 4.70               | 2.32               |
| η Cep         | 0.13               | 0.17               | 2.02           | 0.86           | 2.41               | 1.52               |
| 61 Cyg A      | 0.09               | 0.14               | 1.60           | 0.85           | 2.10               | 0.98               |
| 61 Cyg B      | 0.07               | 0.10               | 1.12           | 0.66           | 1.48               | 0.80               |
| HR 8832       | 0.11               | 0.14               | 1.65           | 0.81           | 2.56               | 1.14               |
| ω Psc         | 0.26               | 0.38               | 4.35           | 1.85           | 4.91               | 2.64               |

* Too few data points for a reliable periodogram search, due to undersampling of eccentric test signals.
we are least sensitive to the most eccentric planets. Nevertheless, for small eccentricities ($e \approx 0.2$), it is possible to combine these dynamical calculations with our companion-limit determinations to define a “safe zone” - a region of parameter space in which we can exclude perturbing giant planets exterior to the habitable zone. For such regions, the possibility of terrestrial planets in the habitable zone remains open for programs such as TPF and Darwin. In Figures 4–11 the region to the left of the dot-dashed line and above the dotted line defines the “safe zone” for perturbing outer giant planets with $e < 0.2$. These were only plotted for main-sequence stars, using the definition of the “continuously habitable zone” given in Kasting et al. (1993). The region left of the dot-dashed line and below our limits represents a set of potentially dangerous objects that would disrupt the habitable zone yet be undetectable with the current data. Higher eccentricities would push the dot-dashed line to the right and reduce its slope, such that for perturbers with $e \approx 0.5$, our limits computations can say nothing about such objects (i.e., the curves would not intersect). The companion limits we have derived thus place some constraints on potentially disruptive objects in these systems, which will assist in target selection for the TPF and Darwin missions.

Noting that the Phase III data are of substantially higher quality than the previous data sets, we asked what velocity rms would be required to rule out a Jupiter analog orbiting a solar-type star. We generated simulated observations consisting of Gaussian noise at the actual observation times (spanning 16 yr) for 16 Cyg A, the star in this study that is closest in spectral type (G1.5 V) to our Sun. Figure 13 shows the results of the companion-limit algorithm on four of these simulated data sets with four levels of rms scatter. In order to rule out a planet with $M \sin i$ of $1 M_J$ in a 5.2 AU orbit ($e = 0.1$), the data need to have an rms less than about 10 m s$^{-1}$. The rms of Phase III observations of 16 Cyg A is 6.9 m s$^{-1}$ over a period of 6.3 yr, whereas the complete 16 yr has an overall rms of 26.8 m s$^{-1}$. Hence, a Jupiter analog could be ruled out for 16 Cyg A with about 10 more years of data of the same quality as McDonald Phase III. The weighted mean rms of all McDonald Phase III observations in this survey is 12.6 m s$^{-1}$. Eleven stars (see Table 2) currently achieve a Phase III rms better than 8 m s$^{-1}$; this represents one-third of the stars discussed in this work. These simulations show that the average precision of Phase III needs to be improved by about 2–3 m s$^{-1}$ in order to achieve the sensitivity required to detect or exclude Jupiter analogs for all of these stars.
5. SUMMARY

We have amassed a substantial quantity of radial velocity data on 31 nearby stars, spanning up to 23 yr of observations. We have applied a robust method to place conservative limits on planetary companions orbiting these stars. We have considered the effect of eccentric orbits in our computations, which better reflects the diversity of known extrasolar planetary systems. Saturn-mass planets within 0.1 AU can be ruled out for nearly all of these stars. At 5.2 AU we can exclude on average planets with $M \sin i \geq (2.0 \pm 1.1)M_J$ ($e = 0$) and $M \sin i \geq (4.0 \pm 2.8)M_J$ ($e = 0.6$) for 25 of the 31 stars. Although we now have a quite sufficient time baseline for the detection of Jupiter analogs in $\sim 12$ yr orbits, we find that the overall velocity precision is not yet sufficient to exclude Jupiter-mass planets at 5.2 AU. However, improvements in the current McDonald Observatory 2.7 m telescope planet search program put the desired level of precision within reach for inactive stars.

This research was supported by NASA grants NNG04G141G and NNG05G107G. R. W. acknowledges support from the Sigma Xi Grant-in-Aid of Research. D. B. P. is currently a National Research Council fellow working at NASA’s Goddard Space Flight Center. We are grateful to Barbara McArthur for her assistance with GaussFit software. This research has made use of NASA’s Astrophysics Data System and the SIMBAD database, operated at CDS, Strasbourg, France, as well as computing facilities at San Diego State University.