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A SEARCH FOR SUBSTELLAR COMPANIONS TO LOW-MASS STARS

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ABSTRACT

We report multiple, precise Doppler measurements (± 230 m s^{-1}) for a sample of 70 low-mass stars, to search for weak gravitational perturbations due to brown drawf companions. The measurements permit detection of any companions having masses above 0.007 $M_\odot$ [$P_{\rm yr}^{1/3}/\sin i$], for orbital periods less than 4 yr. Among the sample stars, all considered single *a priori*, six were found to have *stellar* companions, as found either by large amplitude velocity periodicities or by double lines. The most interesting of these is Gliese 623 which has a companion of mass 0.08 $M_\odot$, based on analysis of the velocities, astrometry, and speckle interferometry, thus placing it at the substellar threshold.

Remarkably, none of the sample stars shows convincing evidence of a substellar companion, despite their easy detection. Long-term astrometric observations provide upper limits to perturbations, showing that the absence of brown dwarfs, with masses as low as 0.02 $M_\odot$, extends to orbital periods of about 30 yr. A similar absence of brown dwarfs is indicated around solar-type stars (Campbell *et al.*). A Scargle periodogram analysis of all velocities revealed three stars, Gliese 380, 521, and 806, that show marginal periodicities significant at the 99% confidence level. The putative companions to these three stars would have masses of approximately 0.01 $M_\odot$ if substantiated.

We discuss the current status of brown dwarf detections by both dynamical and photometric techniques and conclude that, though several candidates exist, there is still no convincing detection to date of an object having mass significantly below 0.08 $M_\odot$. This paucity of detections, especially by dynamical techniques (velocities or astrometry) which are not subject to luminosity selection effects, suggests that the mass distribution of companions to G, K, and M dwarfs declines for masses below about 0.08 $M_\odot$. In addition, brown dwarf companions clearly do not contribute significantly to the local missing mass. Field brown dwarfs may still contribute, but must have a dramatically rising mass distribution compared with companions to stars in order to do so. Finally, the nondetections of companions by dynamical techniques show that the incidence of "planets" that have masses greater than 10 $M_{\rm Jup}$ is less than 2%.

Subject headings: planets: general — stars: binaries — stars: late-type

I. INTRODUCTION

Since the pioneering theoretical work of Kumar (1963*a*, *b*) and Tarter (1975), it has been realized that extremely low mass "stars" might form which would have central temperatures too low to support stable hydrogen burning, because of the onset of electron degeneracy. The existence and properties of such substellar objects ("brown dwarfs") bear on several important astrophysical problems, such as (1) the identification of unseen matter, both in the local Galactic disk (Bahcall 1984) and in halos around other galaxies: (2) the understanding of star formation and protostellar fragmentation at low stellar masses (see Boss 1987); and (3) the determination of masses of primary stars, especially those of lowest mass for which few accurate determinations exist (see McCarthy and Henry 1987 and Liebert and Probst 1987). Further, the existence and prevalence of brown dwarfs may provide information on the condensation processes in massive protostellar disks (e.g., Pollack 1984; Shu, Adams, and Lizano 1987).

Curiously, no confirmed, bona fide substellar objects have been detected, although there are currently two interesting candidates, Gliese 569 (Forrest, Skrutskie, and Shure 1988) and G29–38 (Zuckerman and Becklin 1987*b*). The intrinsic faintness and uncertain surface properties of substellar objects make positive identification by photometric techniques difficult. However, a number of photometric search attempts have been made by Probst and O'Connell (1982), Jameson, Sherrington, and Giles (1983), Probst (1983*a*, *b*), Boeshaar, Tyson, and Seitzer (1986), Chester *et al.* (1988), Shipman (1986), Skrutskie, Forrest, and Shure (1986), Zuckerman and Becklin (1987*a*), and Kumar (1987). The extensive astrometry of hundreds of nearby stars permits detection of perturbations due to companions as small as several Jupiter masses, if the companion exists farther than a few astronomical units from the host star (see Harrington 1986). Yet no convincing detections of substellar objects have resulted (Heintz 1988), and several past claims of such perturbations have been seriously questioned. Multiple radial velocity measurements by Campbell, Walker, and Yang (1988) have also yielded no detections of brown dwarfs.

Here, we report multiple radial velocity measurements for 65 M dwarfs carried out during 4 years in an effort to detect perturbations caused by substellar companions. We combine the velocities with astrometric measurements to yield information on the presence of companions as small as 0.02 $M_\odot$ that are within 10 AU of the target star. The organization of the paper is as follows. Section II describes the sample selection and the spectroscopic observations, which were carried out at both Mount Wilson and Lick Observatories. Sections III*a* and III*b* describe the statistical search for velocity variations, including both obvious cases and the marginal detections.

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Section III*c* contains mass estimates for the marginal detections as well as the detectability limits of the survey as a whole. A discussion of the role of astrometric brown dwarf searches is included. Section IV*a* discusses the current state of knowledge of brown dwarf companions. Sections IV*b* and IV*c* discuss the implications for the local Galactic missing mass and for the formation of low-mass stellar companions.

II. OBSERVATIONS

a) Sample Selection

We have chosen a sample of nearby M dwarfs as target stars for several reasons. First, their low inertia ($M \approx 0.35\ M_{\odot}$) implies greater reflex velocities for companions of a given mass. Second, their optical spectra contain a high density of narrow, deep absorption lines and thus are ideal for cross-correlation techniques designed to extract Doppler shifts. Third, the luminosities of M dwarfs are 20–100 times less than those of solar-type stars, thus significantly improving the thermal survivability of very nearby (less than 1 AU) substellar companions (Black and Scargle 1982). Finally, M dwarfs may theoretically be preferred sites of formation of substellar objects based on the results of herarchical protostellar fragmentation in which mass ratios near unity are favored (Boss 1987). As target stars, M dwarfs carry one significant disadvantage in that they are typically faint for high-dispersion spectroscopy.

The sample was chosen from the list of Joy and Abt (1974) with the selection criteria that the dwarfs have spectral types later than dM2 (though several bright M0 dwarfs were included), declinations between $-20°$ and $+50°$, and that they be brighter than $V = 11.5$. All stars with known companions within 10″ were rejected as they would show variable radial velocities, would provide a less stable environment for a substellar object, and would be difficult to isolate reliably on the slit of the spectrograph. The final stellar sample consists of 71 stars. A magnitude-limited subset of these, defined as those brighter than $V = 10.5$, having $\delta > 0°$, and later than dM2, represents 80% of all such stars listed in the Gliese catalog (Gliese 1969). These stars all lie within 15 pc of the Sun, a region in which most, if not all, M dwarfs brighter than $V = 10.5$ have now been identified (Gliese, Jahreiss, and Upgren 1987). Thus, this subset suffers little kinematic bias (unlike some proper-motion-selected samples) and hence contains little bias in age and metallicity.

b) Technique and Reduction of Velocities

The radial velocity acquisition began at the Mount Wilson Observatory 2.5 m telescope in 1983 June and has continued at Lick observatory since 1986. At Mount Wilson, the 114 inch (2.9 m) coudé spectrograph was used with a Bausch and Lomb, 600 g mm^{-1} grating blazed at 6000 Å in fourth order, yielding a reciprocal dispersion of 1.0 Å mm^{-1}. The intensified Reticon detector "Shectograph" (Shectman 1981), was used because it produces essentially no noise and is therefore ideal for the anticipated low signal-to-noise ratio of faint M dwarf spectra. This system yielded 500 m s^{-1} per pixel. Several significant structural modifications were made to ensure stability of the optical system during the course of a night, primarily in the support for the detector and grating. Careful measures were taken to ensure that the calibration sources match the optical axis and f-ratio of the telescope.

A small slit (0″.35) was used to reduce systematic errors due to nonuniform illumination of the slit (see Griffin and Griffin 1973). The integration times for these stars, having $V = 9$ to $V = 12$, were typically 30 minutes, and the resulting spectra had a signal-to-noise ratio of only about 5–10 per pixel and covered from 5578 to 5604 Å. Calibration Th-Ar spectra were obtained both before and after each observation to correct for drifts in the detector on time scales of hours. A description of the procedure by which the raw spectra were reduced and Doppler shifts extracted has been previously given (Marcy, Lindsay, and Wilson 1987).

The shifts were determined by a cross-correlation scheme, using a composite M dwarf spectrum (M2–M5) as a template. These velocities contained night-to-night systematic errors of several hundred meters per second, presumably due to differences in the optics of the telescope, spectrograph, and calibration lamps. Therefore, we applied a uniform correction to each velocity measurement on a given night equal to the average of the residuals between the long-term average velocities and those in the current set. Typically, 20 stars were observed per night, yielding an uncertainty in the nightly correction of about 40 m s^{-1} ($\sigma/N^{1/2}$), as the internal errors are about 150 m s^{-1}. The zero-point of the velocity measurements was established by high-resolution spectra of a small subsample of stars (Marcy, Lindsay, and Wilson 1987) and has an uncertainty of 0.4 km s^{-1}.

With the closing of the 2.5 m telescope at Mount Wilson, we continued observations at Lick Observatory, using the coudé echelle ("Hamilton") spectrometer (Vogt 1988) and TI CCD detector. This system collects 53 spectral orders simultaneously, each covering about 40 Å, with the total wavelength range being $\lambda = 4900$–8000 Å. Each pixel corresponds to 2.5 km s^{-1}, and the typical signal-to-noise ratio was about 20. Both the 3 m and 0.6 m coudé auxiliary telescopes were used, requiring integration times of about 10 minutes for the former (at $V = 10$), and about 60 minutes for the latter. The slit width was 0″.6 to reduce spurious spectrum shifts due to nonuniform illumination of the slit.

The Lick data were reduced differently than those obtained at Mount Wilson. The raw spectra were "flat-fielded" with exposures of an incandescent lamp located on the polar axis, but no wavelength calibration was ever done. For measurement of the Doppler shifts, a high-quality observation of 61 Cygni B (Gliese 820B) was obtained to serve as a template for each observing run. Tests showed that its dM0 spectral type was sufficiently close to those of the program stars (M2–M5) to ensure that spectral differences (i.e., asymmetric molecular features) did not induce systematic errors in the cross-correlation shift. We tested for this by comparing the shifts obtained from different orders and found no significant differences in the shift as a function of spectral type.

The final Doppler shift measurement made use of only seven spectral orders out of the 53, chosen on the basis of having many strong and sharp stellar absorption features and on being void of telluric features. For each program star, these orders were cross-correlated against the template which was obtained on the same run. We then cross-correlated the two spectral orders that contained essentially pure telluric features, namely the A and B band head regions. These absorption features should be formed in the rest frame of the observatory (in error by the atmospheric wind speed) and therefore provide a relatively stable velocity reference, similar to that used by Smith (1983). By subtracting the telluric shift from the star shift we established a net shift relative to 61 Cyg B that is immune to the various systematic effects known to contaminate conventional radial velocity determinations (Campbell and Walker 1979).

This net shift *in pixels* is directly related to the topocentric velocity of the star at the time of observation. However, the expected *heliocentric* velocity of all program stars is already known from two years of intensive monitoring (Marcy, Lindsay, and Wilson 1987). These velocities, corrected for Earth's orbital and rotational motion, yield topocentric velocities which correlate extremely well with the measured net pixel shift. (Thanks are due to Michael deRobertis for the orbital correction software based on the work of Stumpff 1980.) A parabolic fit between pixel shift and topocentric velocity was constructed for about 10 well-observed stars each run, thus establishing the velocity calibration for the run. The rms of the residuals to this fit was typically 200 m s^{-1}, which we consider to be the internal error of the Lick velocities. This error is essentially the same as the internal error for the Mount Wilson velocities (150 m s^{-1}), by design, as both internal errors are dominated by photon statistics. The final heliocentric velocities for all program stars were derived by using the parabolic fit to convert net pixel shifts to topocentric velocities, and correcting them to the solar system barycenter.

c) *The Final Velocities*

The journal of observations is given in Table 1 and shows the Julian Dates and all measured velocities for all stars on this program. All observations dated after JD = 2,446,300 were made at Lick. The integrity of any radial velocities derived by cross-correlation, such as these, are subject to possible spectral type–dependent effects. Here we have a fortuitous opportunity to search for such effects by using the very different wavelength regions covered in the Mount Wilson and Lick spectra. Comparison of the Lick velocities to those from Mount Wilson showed no significant differences as a function of spectral type. Even for the extreme case, Barnard's star, which is very cool (dM5, hence having relatively strong molecular bands) and which has a large negative velocity, the average of three Lick velocities was -110.83 km s^{-1} compared with the average of the Mount Wilson velocities of -110.86 km s^{-1}, a negligible difference. The data also show that the external uncertainty of the Lick velocities is about the same as that from Mount Wilson, based on the observed variance from the two sites. We conclude that the Lick velocities are comparable in precision and are on the same scale (by construction) as those obtained at Mount Wilson.

The precision of all the velocities may be judged by the variance in the measurements for stars which are thought to be single. Two such stars, Gliese 820A and Gliese 699 (Barnard's) are sufficiently close that astrometry can place stringent upper limits on the mass of any companions within a few AUs of the star. According to Heintz (1988), these two stars show no trace of perturbation at the level of $0\farcs015$, over decades. This null result shows that no companions of a few Jupiter masses or more can exist near them. Campbell, Walker, and Yang (1988) find the same result for Gliese 820A from their more precise velocities. In the present data, the velocities of these two stars exhibit standard deviations of 0.22 km s^{-1} and 0.24 km s^{-1}, respectively (see Table 2). *Thus the best estimate of the velocity precision is* about *0.23* km s^{-1}. Indeed, the average standard deviation of all stars, excluding those showing clear velocity variations, is 0.23 km s^{-1}. A complete discussion of the sources of error is given in an earlier paper (Marcy, Lindsay, and Wilson 1987). Table 2 contains a summary of all Doppler measurements. From left to right, the columns give the star name, number of observations, the average velocity, and the standard deviation, respectively. The fifth column gives the number of days between first and last observations.

III. ANALYSIS OF THE VELOCITIES

a) *Obvious Velocity Variations and the F-Test*

The velocity data set consists of multiple measurements for each of 65 stars, spanning typically three to four years. (Note that four stars, GL 206, GL 268, GL 735, and GL 289 show double lines (Marcy, Lindsay, and Wilson 1987) and hence are not included in this discussion.) Inspection of all velocities reveals only two stars, GL 623 and GL 570B, with obvious velocity variations.

GL 623 exhibits clear variations with amplitude 1.9 km s^{-1} and a period of 3.7 yr. Combining available astrometric and speckle interferometric observations (Lippincott and Borgman 1978 and McCarthy and Henry 1987) shows that the companion has a mass of 0.080 ± 0.01 $M_\odot$, as discussed previously (Marcy and Moore 1989).

GL 570B shows dramatic velocity variations over the 4 years of observations. The measurements are shown in Figure 1, along with a least-squares orbital fit calculated kindly by David Moore. The orbital elements are $P = 308\overset{d}{.}2$, $V_{bary} = 29.1$ km s^{-1}, $T_0 = 2445948$, $e = 0.76$, $a \sin i = 0.318$ AU, and $\omega = 130°$. The mass function then is $M_2^3 \sin^3 i/(M_1 + M_2)^2 = 0.045$ $M_\odot$. Assuming the primary has a mass of 0.35 $M_\odot$, typical for its spectral type, the minimum mass for the companion is 0.25 $M_\odot$, well above the hydrogen-burning threshold. We have searched for double absorption lines by direct inspection and by an autocorrelation scheme, giving special scrutiny to spectra obtained at times of expected large velocity separation. However, no clear evidence of the secondary lines was found, yielding an upper limit on the brightness (at 5000 Å) of the companion of one-tenth that of the primary. The nondetection of secondary lines is surprising, as the mass estimates imply that the companion should be no fainter than one-sixth as bright as the primary (Liebert and Probst 1987).

For the remaining stars in the sample, subtle velocity variations may be found by an F-ratio test that is sensitive to variances that are significantly higher than expected by random errors (e.g., Young, Sadjadi, and Harlan 1987). Table 2 gives the standard deviations of the velocities for all stars in the sample. For the F-test, we have adopted 230 m s^{-1} as the random error, based on known single stars, as discussed in § II*c*. We set a 99% significance threshold for the F-test so that a claimed detection would occur in only 1% of the data sets owing to radom errors alone. Application of the F-test to GL 623 and GL 570B indicated clearly that they were velocity variables, in agreement with their obvious variations.

However, no other star had a sufficiently high F-statistic to indicate that its variance would occur less than 1% of the time just by chance. *That is, no statistically significant velocity variables were found by the F-test.* The closest case is GL 806 for which nine measurements yielded an F-statistic of 2.1 ($\sigma = 0.49$ km s^{-1}). This is short of the required ratio of 2.7 necessary for the 1% statement. Its F-statistic *is* high enough however to satisfy a 5% threshold, so it should occur by chance in only one

TABLE 1

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JD − 2440000	V ($km s^{-1}$)	JD − 2440000	V ($km s^{-1}$)	JD − 2440000	V ($km s^{-1}$)	JD − 2440000	V ($km s^{-1}$)	JD − 2440000	V ($km s^{-1}$)
GL 14		6666	-2.50	GL 206		5813	19.59	6064	12.38
5547	3.45	GL 107B		5725	5.76	5847	19.87	6065	12.92
5588	2.83	5547	25.76	GL 213		6028	19.91	6076	12.28
5675	3.40	5588	26.33	6064	105.57	6063	20.15	6079	12.38
5724	3.40	5648	26.10	6076	105.38	6065	19.47	6113	12.66
5886	3.22	5674	26.02	6113	105.25	6076	19.90	6140	12.24
5910	3.76	5703	25.62	6141	105.20	6079	20.08	6142	12.35
5933	3.87	5724	25.88	GL 229		6112	20.05	6178	12.32
6028	3.27	5754	25.93	5589	4.44	6141	20.34	6210	12.27
6064	3.42	5911	26.16	5674	4.33	6178	19.91	6591	12.43
6065	3.28	6028	25.84	5703	4.60	6210	19.82	6872	12.60
6077	3.51	6064	26.44	5723	4.48	GL 361		6900	12.12
6079	2.77	6079	25.93	5754	4.62	5675	11.26	GL 393	
6239	2.95	6112	25.74	6027	4.51	5703	11.71	5675	8.16
6629	3.12	GL 109		6029	4.59	5724	11.37	5703	8.86
6666	3.33	5589	30.24	6063	4.50	5754	11.58	5724	8.37
GL 15A		5674	30.20	6064	4.89	5790	11.54	5754	7.85
5589	12.25	5703	30.11	6076	4.62	5847	11.52	5790	8.15
5675	11.97	5912	30.74	6077	4.65	6064	11.17	5813	8.44
5703	11.74	6028	30.47	6079	5.00	6079	10.90	5846	8.25
5886	11.92	6064	30.12	6112	4.86	6113	11.81	6063	8.29
5910	12.20	6076	30.53	6142	4.21	6142	11.70	6076	8.15
5932	12.17	6113	30.34	GL 251		6178	11.78	6112	8.71
6064	11.73	6629	30.58	5674	22.80	6212	11.54	6113	8.39
6077	11.58	GL 173		5703	22.38	6872	11.60	6140	8.43
6113	11.95	5589	-6.99	5724	22.82	GL 369		6178	8.57
6240	12.19	5648	-7.28	5754	23.13	5674	62.57	6211	8.42
6590	11.91	5676	-6.85	5790	22.62	5703	62.42	6872	8.30
GL 15B		5703	-6.95	6028	22.67	5724	62.11	GL 402	
5589	11.06	5725	-6.96	6029	22.57	5754	61.79	6142	-1.09
5676	10.93	5754	-7.15	6063	22.63	5790	61.71	GL 411	
5725	10.89	6027	-7.08	6064	22.76	5813	62.50	5675	-84.47
5910	11.31	6063	-7.55	6076	23.00	5847	61.65	5703	-84.69
6028	10.88	6065	-6.98	6079	22.72	6027	62.24	5724	-84.80
6064	10.94	6076	-6.62	6112	22.59	6063	61.97	5751	-84.67
6242	10.84	6079	-6.36	6178	22.74	6065	62.34	5754	-84.40
GL 26		6112	-7.19	GL 273		6076	62.31	5790	-84.72
5547	-0.46	6140	-7.29	5674	17.87	6112	62.19	5813	-84.88
5588	-0.15	6142	-7.05	5676	18.03	6141	62.06	5845	-84.70
5674	-0.41	GL 176		5703	18.66	6178	62.00	6027	-84.93
5912	-0.33	5588	25.88	5723	18.21	6211	62.48	6064	-85.00
6028	-0.01	5648	26.21	5724	18.06	6872	62.07	6076	-84.96
6079	-0.48	5674	25.99	5754	17.95	GL 380		6079	-84.57
6241	-0.12	5703	25.57	5790	18.04	5675	-25.81	6112	-84.80
6629	0.14	5724	26.28	5813	17.82	5703	-25.37	6113	-84.81
GL 33		5754	25.64	6027	18.33	5724	-25.13	6141	-84.69
6028	-9.56	6027	26.25	6029	18.07	5754	-24.58	6142	-84.63
6065	-9.64	6029	26.07	6063	18.58	5813	-25.38	6175	-84.70
6076	-9.99	6063	25.87	6064	17.85	5845	-25.21	6210	-84.79
6079	-9.78	6064	25.87	6065	18.40	5846	-25.08	6237	-84.83
6112	-9.63	6077	26.04	6076	17.82	6027	-25.74	6591	-84.37
6239	-9.77	6079	25.94	6079	17.95	6028	-25.30	6629	-84.25
6628	-9.24	6113	25.86	6112	17.90	6029	-25.62	6872	-84.84
GL 70		6141	26.17	6872	18.89	6063	-25.20	GL 412A	
5676	-26.01	GL 179		GL 285		6064	-25.43	5676	68.63
5725	-26.32	5674	-8.98	5674	26.90	6065	-25.34	5724	68.78
5911	-26.32	6028	-9.27	5724	26.58	6079	-25.49	5751	68.71
6028	-26.00	6141	-9.03	5754	26.96	6112	-24.97	5813	68.65
6064	-25.93	GL 205		5790	26.26	6113	-25.13	5845	69.30
6079	-25.93	5589	8.26	6028	26.58	6141	-25.08	6027	69.25
6113	-25.62	5648	8.45	6063	26.54	6175	-25.20	6064	68.94
6242	-26.18	5674	8.30	6064	26.51	6178	-25.52	6079	69.03
6629	-25.78	5703	8.70	6076	26.46	6210	-25.26	6113	68.74
GL 87		5723	8.53	6112	26.52	6591	-25.17	6141	69.02
5589	-2.94	5725	8.26	6872	27.52	6872	-25.63	6142	69.24
5674	-2.92	5754	8.23	GL 289		6900	-25.96	6175	68.94
5703	-2.74	6027	8.42	6065	40.44	GL 388		6210	68.89
5912	-2.21	6029	8.77	6113	52.51	5675	12.23	6238	69.03
6028	-2.50	6064	8.22	6142	52.42	5703	12.29	6629	68.81
6064	-3.06	6065	8.71	GL 353		5724	12.32	6872	68.89
6065	-2.84	6076	8.62	5674	19.82	5751	12.41	GL 414A	
6076	-2.66	6077	8.56	5703	20.00	5790	12.23	5675	-15.50
6077	-2.71	6079	8.75	5724	19.99	5813	12.02	5703	-15.91
6112	-3.15	6112	8.63	5754	20.43	5845	12.28	5724	-15.54
6629	-2.38	6142	8.98	5790	19.80	6029	12.58	5753	-15.55

Table 1—*Continued*

JD – 2440000	V (kms^{-1})
5790	-15.82
5813	-15.96
5845	-15.51
6063	-15.63
6112	-15.68
6140	-15.62
6175	-15.96
6212	-15.71
6239	-15.94
6629	-15.52
6629	-15.52
6872	-15.72
GL 414B	
5675	-14.69
5676	-15.46
5724	-15.25
5753	-15.09
5790	-15.18
5845	-15.23
6063	-14.89
6112	-15.38
6140	-15.16
6178	-15.44
6212	-14.92
6238	-15.56
6629	-15.06
6872	-15.13
GL 436	
5725	9.71
5754	9.50
5790	9.42
5846	9.77
6064	9.76
6112	9.55
6141	9.68
6178	9.74
6210	9.57
6240	9.78
6629	9.76
6900	9.43
GL 447	
5724	-31.52
5754	-31.23
5846	-31.37
6065	-31.47
6112	-31.08
6140	-30.87
6212	-31.61
6872	-31.53
GL 459.3	
5725	-0.37
5753	-0.63
5813	-0.96
5845	-0.82
6064	-0.71
6113	-0.57
6140	-0.36
6178	-0.88
6211	-0.31
6239	-1.00
6629	-0.85
6872	-0.56
GL 461	
5725	4.34
5751	3.80
5790	4.08
5846	3.88
6065	4.01
6112	3.90
6141	3.71
6178	3.79
6211	4.06
6241	4.15
6900	4.20
GL 464	
5724	6.75
5754	6.66
5845	6.52
6064	6.76
6113	6.72
6140	7.00
6178	6.93
6212	6.71
6239	7.19
6872	6.84
GL 480	
5754	-4.62
5813	-4.12
5846	-4.20
6065	-4.36
6112	-4.14
6141	-4.65
6210	-4.16
6241	-3.99
6900	-4.13
6900	-4.19
GL 486	
6142	19.20
GL 507.1	
5725	-11.74
5753	-11.16
5790	-11.46
5845	-12.29
5886	-11.92
5911	-11.77
5912	-11.68
5933	-11.38
5934	-11.75
6063	-11.78
6064	-11.77
6079	-11.68
6112	-12.06
6113	-11.63
6142	-11.15
6178	-12.06
6210	-11.63
6238	-11.58
6239	-11.65
6628	-11.94
6872	-11.38
GL 521	
5725	-65.32
5751	-64.55
5754	-64.08
5846	-65.02
5886	-65.71
5911	-65.30
5912	-64.91
5933	-65.30
5934	-65.58
6064	-65.49
6065	-65.63
6079	-65.18
6112	-65.23
6140	-65.28
6141	-64.97
6175	-65.36
6178	-65.26
6210	-65.06
6240	-65.16
6628	-65.14
6872	-65.06
GL 526	
5516	15.77
5545	15.61
5724	15.72
5725	15.73
5751	15.80
5753	15.61
5790	16.08
5813	15.69
5846	15.38
5847	15.59
6065	15.93
6113	15.74
6140	15.58
6175	15.62
6177	15.62
6211	15.71
6212	15.73
6237	15.52
6628	15.61
6871	16.21
6900	15.65
GL 552	
5754	7.64
5846	7.69
5912	7.38
6113	7.17
6178	7.90
6210	7.84
6239	7.56
6666	8.00
6900	8.04
GL 569	
5725	-7.06
5753	-7.35
5790	-6.98
5813	-6.60
5846	-7.03
5912	-7.37
6065	-7.28
6112	-7.13
6141	-7.25
6177	-7.22
6211	-7.74
6237	-6.99
6629	-7.53
6666	-7.11
6900	-6.85
GL 570B	
5726	27.52
5754	28.89
5791	31.22
5814	32.78
5846	34.39
5848	33.96
5912	38.11
6066	29.34
6080	29.89
6113	31.92
6141	33.58
6176	36.25
6212	37.77
6238	37.92
6240	36.97
6242	36.14
6629	24.57
6666	28.53
6872	15.01
6900	15.77
7182	8.80
7195	9.60
7224	22.00
GL 570.2	
5847	7.90
6113	7.82
6142	6.91
6178	8.23
6210	8.07
6239	7.48
6628	7.94
6666	7.95
6872	7.59
6900	7.53
GL 581	
5754	-9.42
5846	-9.55
5911	-8.92
6113	-9.59
6140	-9.72
6211	-9.34
6237	-9.39
6629	-9.94
6666	-9.29
6900	-9.09
GL 623	
5519	-28.15
5547	-28.48
5548	-28.16
5589	-29.20
5726	-29.77
5752	-29.18
5754	-29.63
5814	-29.35
5846	-28.54
5847	-28.79
5887	-26.94
5911	-26.39
5934	-25.90
5935	-26.26
6113	-25.63
6141	-26.05
6179	-25.99
6211	-26.32
6238	-26.49
6241	-26.49
6242	-26.94
6591	-27.06
6628	-28.14
6629	-27.62
6666	-27.86
6871	-28.54
6872	-28.11
6900	-28.66
GL 638	
5517	-31.25
5547	-30.87
5586	-31.17
5725	-31.36
5751	-30.95
5753	-31.15
5790	-31.10
5813	-30.96
5845	-31.31
5847	-30.59
5911	-31.32
5932	-30.80
5934	-31.51
6113	-31.20
6142	-30.85
6175	-31.38
6211	-31.12
6212	-30.97
6238	-30.98
6240	-31.24
6628	-31.30
6666	-31.19
6871	-31.00
6900	-31.43
GL 649	
5516	4.24
5517	4.51
5545	4.24
5589	4.30
5753	4.45
5790	4.51
5813	4.40
5845	4.20
5912	4.15
5933	4.16
5934	4.58
6140	4.02
6175	4.39
6211	4.18
6237	4.63
6241	4.22
6628	3.70
6629	3.90
6666	4.48
6900	4.40
GL 654	
5518	34.78
5546	34.77
5586	34.59
5754	34.47
5790	34.84
5813	34.80
5845	34.60
5911	34.40
5933	34.37
6140	34.55
6175	34.84
6210	34.65
6238	34.39
6240	34.30
6666	34.55
6900	34.69
GL 694	
5845	-13.75
5912	-13.77
5933	-14.18
6212	-14.14
6238	-14.02
6240	-14.25
6628	-14.05
6666	-14.26
6900	-14.19
GL 699	
5516	-110.78
5517	-110.97
5545	-110.61
5588	-110.78
5589	-110.70
5753	-110.97
5754	-110.79
5790	-110.31
5813	-110.94
5845	-111.05
5847	-110.83
5886	-110.62
5911	-111.41
5932	-110.76
5934	-111.23
6113	-111.01
6142	-110.88
6177	-110.59
6210	-111.02
6237	-110.79
6238	-110.74
6241	-111.11
6628	-110.98
6666	-110.68
6900	-110.82
GL 701	
5517	32.72
5547	32.36
5589	32.48
5813	32.94
5845	32.47
5846	32.63
5886	32.36
5912	31.84
5933	32.27
5934	32.12

TABLE 1—*Continued*

JD – 2440000	V (kms^{-1})	JD – 2440000	V (kms^{-1})	JD – 2440000	V (kms^{-1})	JD – 2440000	V (kms^{-1})	JD – 2440000	V (kms^{-1})
6175	32.73	6666	-42.41	6238	-64.86	6900	-64.06	GL 875.1	
6210	32.22	6900	-41.75	6239	-64.70	GL 831		5912	-1.59
6238	32.49	GL 752A		6240	-65.09	6666	-57.06	GL 876	
6240	32.90	5516	36.01	6241	-64.94	GL 849		5546	-1.79
6241	32.46	5517	35.97	6242	-64.82	5676	-15.14	5547	-1.59
6629	32.58	5546	35.79	6628	-65.13	5847	-15.23	5589	-1.91
6666	32.23	5586	35.87	6629	-65.00	5911	-15.51	5676	-1.67
6900	32.59	5845	35.85	6666	-65.11	6028	-15.33	5910	-2.28
GL 720A		5847	35.70	6871	-64.76	6239	-15.77	5933	-2.29
5518	-31.09	5911	35.78	6871	-64.89	6629	-15.16	6065	-1.59
5545	-31.11	5932	35.53	6872	-64.63	GL 851		6237	-1.94
5586	-31.14	5934	35.55	6900	-65.05	5546	-51.57	6240	-1.49
5845	-30.94	6028	36.05	GL 820B		5588	-51.45	6629	-1.13
5911	-31.30	6177	36.09	5517	-63.88	5675	-51.13	GL 880	
5934	-31.14	6237	35.71	5545	-63.83	5846	-51.60	5516	-27.62
6177	-31.17	6238	35.94	5586	-63.86	5886	-51.35	5517	-27.71
6211	-30.93	6242	35.70	5675	-63.95	5911	-51.65	5545	-27.43
6238	-31.18	6666	35.73	5845	-63.95	5932	-51.34	5589	-27.24
6240	-31.25	6900	35.85	5886	-63.81	5934	-51.03	5674	-27.10
6628	-31.20	GL 806		5910	-64.10	6064	-50.76	5847	-27.46
6666	-31.54	5547	-24.12	5911	-63.93	6237	-51.57	5910	-27.34
6900	-31.22	5589	-23.90	5912	-63.79	6240	-51.59	5932	-27.23
GL 745A		5846	-24.40	5932	-63.86	6629	-51.32	5934	-26.94
5846	32.78	5911	-23.28	5933	-63.75	6666	-51.64	6028	-27.22
5886	32.05	6065	-24.30	5934	-63.66	GL 863		6064	-27.24
5910	32.16	6239	-24.16	6028	-63.97	5675	-6.61	6237	-27.54
5933	32.18	6629	-24.55	6065	-63.97	5886	-6.46	6238	-27.47
6028	31.80	6666	-24.51	6175	-63.95	5911	-6.22	6629	-27.20
6211	32.25	6900	-25.06	6177	-63.97	5932	-6.50	GL 905	
6239	32.36	GL 820A		6178	-64.08	6028	-6.23	6241	-77.58
6241	32.22	5886	-64.83	6211	-64.06	6238	-6.35	GL 908	
6666	31.97	5910	-64.60	6237	-63.72	6241	-6.46	5518	-71.42
6900	32.37	5911	-64.75	6238	-63.84	6628	-6.52	5545	-71.21
GL 745B		5912	-64.81	6239	-63.77	6666	-6.15	5588	-71.07
5886	31.83	5932	-65.39	6240	-63.95	GL 873		5674	-71.13
5910	31.42	5933	-65.02	6241	-64.05	5545	0.37	5886	-71.19
5933	32.14	5934	-64.76	6242	-63.64	5588	0.43	5910	-71.40
6239	32.29	6028	-65.03	6589	-64.05	5676	0.51	5932	-71.19
6241	31.82	6065	-65.21	6591	-64.29	5886	0.51	6064	-71.03
6628	32.30	6175	-65.01	6628	-63.77	5912	0.31	6237	-71.18
6666	31.74	6177	-65.27	6629	-63.97	5933	0.84	6629	-71.14
6900	32.23	6178	-65.14	6666	-64.15	6028	0.20	–	
GL 748		6211	-65.24	6871	-63.33	6065	0.23	–	
6628	-42.42	6237	-64.89	6872	-63.29	6239	0.86	–	

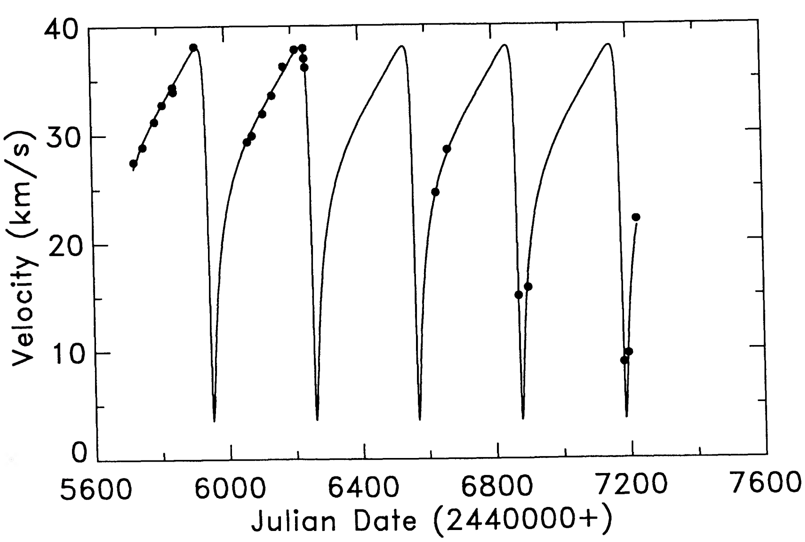

FIG. 1.—The velocity curve of Gliese 570B. Filled circles represent the observed velocities and the solid line represents the least-squares orbital fit, giving $P = 308^d$, $e = 0.76$, and $a_1 \sin i = 0.32$ AU. The minimum mass for the companion is $0.25\, M_{\odot}$.

TABLE 2

SUMMARY OF VELOCITY RESULTS

Gliese #	N obs	V_{avg} kms^{-1}	σ kms^{-1}	ΔT days	F.Alarm Prob. %	Gliese #	N obs	V_{avg} kms^{-1}	σ kms^{-1}	ΔT days	F.Alarm Prob. %
14	15	3.31	0.30	1118	15.5	480	10	-4.26	0.22	1145	86.7
15A	11	11.97	0.22	1000	34.1	486	1	19.20	...	0	...
15B	7	10.98	0.16	653	97.8	507.1	21	-11.69	0.28	1146	41.7
26	8	-0.23	0.23	1081	97.0	521	21	-65.17	0.36	1146	0.8
33	7	-9.66	0.23	600	84.5	526	21	15.71	0.18	1383	94.3
70	9	-26.01	0.23	952	54.0	552	9	7.69	0.29	1145	57.9
87	12	-2.72	0.28	1076	3.6	569	15	-7.17	0.28	1174	53.2
107B	12	25.98	0.25	565	60.6	570B	20	30.63	7.68	1173	0.0
109	9	30.37	0.22	1039	68.4	570.2	10	7.74	0.38	1052	76.5
173	14	-7.02	0.29	553	12.8	581	10	-9.42	0.30	1145	33.2
176	14	25.97	0.21	553	99.0	623	28	-27.67	1.27	1381	0.0
179	3	-9.10	0.16	467	97.1	638	24	-31.12	0.22	1382	100.0
205	16	8.52	0.23	553	92.7	649	20	4.28	0.23	1383	61.5
206	1	5.76	...	0	...	654	16	34.60	0.18	1381	92.8
213	4	105.35	0.17	77	98.3	694	9	-14.07	0.19	1054	94.5
229	14	4.59	0.22	553	87.5	699	25	-110.85	0.23	1383	100.0
251	13	22.72	0.19	504	74.4	701	18	32.47	0.28	1382	27.1
273	17	18.14	0.32	1197	23.5	720A	13	-31.17	0.15	1381	99.5
285	10	26.68	0.36	1197	2.4	745A	10	32.21	0.26	1053	24.2
289	3	48.45	(6.94)	77	...	745B	8	31.97	0.32	1013	30.5
353	16	19.95	0.24	536	48.1	748	3	-42.19	0.38	272	24.1
361	13	11.50	0.26	1196	57.7	752A	16	35.82	0.17	1384	98.7
369	16	62.15	0.28	1197	92.3	806	9	-24.25	0.49	1353	0.04
380	23	-25.33	0.30	1224	0.7	820A	26	-64.96	0.21	1014	63.2
388	20	12.37	0.20	1224	97.1	820B	32	-63.88	0.21	1383	89.9
393	15	8.36	0.24	1196	94.2	831	1	-57.06	...	0	...
402	1	-1.09	...	0	...	849	6	-15.36	0.24	952	62.2
411	22	-84.70	0.19	1196	75.2	851	13	-51.38	0.27	1119	40.0
412A	16	68.93	0.21	1195	98.5	863	9	-6.39	0.16	990	99.9
414A	16	-15.69	0.17	1196	100.0	873	9	0.47	0.24	694	74.0
414B	14	-15.17	0.24	1196	100.0	875.1	1	-1.59	...	0	...
436	12	9.64	0.14	1174	100.0	876	10	-1.77	0.36	1082	1.7
447	8	-31.34	0.26	1147	65.2	880	14	-27.34	0.21	1112	26.2
459.3	12	-0.67	0.24	1146	85.6	905	1	-77.58	...	0	...
461	11	3.99	0.20	1174	83.3	908	10	-71.20	0.13	1110	100.0
464	10	6.81	0.19	1147	90.7						

out of 20 data sets. Since there are 60 stars being considered, we expect a few to have such an F-statistic. We note that GL 806 has a reported astrometric perturbation (Lippincott 1979), but W. Heintz (personal communication), also at Sproul Observatory, has recently reported that the evidence for astrometric perturbations is not strong. We note that another star, GL 289, has a large formal standard deviation (6.9 km s^{-1}) based on only three measurements, one of which is greatly different from the other two. We thus discount that one measurement, pending future observations.

b) *Periodogram Search*

The F-test is not the most robust test of velocity variations, as it is not sensitive to embedded periodicities or trends in the time series. Therefore, we also search for velocity variations using the periodicity analysis developed by Scargle (1982), which is applicable for unevenly sampled measurements. Prescriptions for this analysis are given by Horne and Baliunas (1986) and Gilliland and Baliunas (1987).

The normalized periodogram function defined by Scargle (1982) and Horne and Baliunas (1986) is

$$P_N(\omega) = \frac{1}{2\sigma^2}\left\{\frac{[\sum_j X_j \cos \omega(t_j - \tau)]^2}{\sum_j \cos^2\omega(t_j - \tau)} + \frac{[\sum_j X_j \sin \omega(t_j - \tau)]^2}{\sum_j \sin^2\omega(t_j - \tau)}\right\} . \quad (1)$$

Here, τ is given by

$$\tau = \frac{1}{2\omega} \tan^{-1}\left(\frac{\sum_j \sin 2\omega t_j}{\sum_j \cos 2\omega t_j}\right) , \quad (2)$$

and X_j represents the individual measurements, ω is the test angular frequency, σ is the total variance of the data, and j takes on integer values up to the total number of observations, N. We have assigned equal weight to all observations since their quality was nearly uniform. For σ we have adopted a uniform value of 0.23 km s^{-1}, as discussed in § II *c*.

Assuming that the data are pure noise, the probability that some peak in the periodogram function has a height p_0 or higher is the *false alarm probability* (Scargle 1982) and is given by

$$\mathrm{Pr} = 1 - (1 - e^{-p_0})^{N_i} . \quad (3)$$

Here N_i is the number of independent frequencies which depends on both the average spacing in time between the measurements and on the clumpiness of the sampling in time. To determine N_i for our particular sampling, we generated synthetic data sets that had the same temporal sampling as our actual observations, but which contained only Gaussian noise representative of our actual errors. We constructed thousands of these pseudorandom data sets, computed the periodogram function for each, and established the resulting distribution of maximum peak heights. Comparing this distribution to the theoretical distribution (eq [3]) allowed us to solve for the value of N_i appropriate to our sampling. We found that N_i was well represented by 1.15N, where N is the number of observations. This may be compared with the analytic relation for N_i found by Horne and Baliunas (1986) for nearly *evenly* sampled data, viz., $N_i = -6.4 + 1.19N + 0.00098N^2$.

The resulting false alarm probabilities for all stars are given in Table 2. As expected, GL 570B and GL 623 have false alarm probabilities of 0.00, with periodogram peaks located at their known orbital periods. In addition, we find three stars, GL 380, GL 521, and GL 806 that have false alarm probabilities less than 1%. (Here we exclude GL 289 which has only three observations.) Since there are about 60 stars in our sample, we would expect typically at most one to yield a false alarm at the 1% level simply due to random fluctuations. Thus, these three stars are the only low-amplitude spectroscopic binary candidates in the survey. The periodogram peaks were found at 122^d, 510^d, and 416^d, respectively, for those three stars, though the possibility of aliasing longer periods makes these periods of dubious value.

Inspections of the velocity data sets for those three candidate stars indicates the reasons for their low false alarm probabilities: they all have rather high standard deviations, above 300 m s^{-1}, and they show evidence of coherence in the velocity variations with time, as is evident in a phased presentation of the data. For example, Figure 2 shows the phased velocities for the most compelling of the three cases, GL 380. We assume an orbital period of $122\overset{d}{.}5$, corresponding to the highest amplitude found in the periodogram analysis. This phased diagram exhibits evidence of sinusoidal velocity variability with an amplitude that is only slightly greater than the measurement uncertainty, 230 m s^{-1}. Despite this visually apparent variability as well as the low false alarm probability (0.7%) for GL 380, we choose to interpret these data as only marginal evidence of periodicity, pending more precise measurements. Similarly, we consider the velocity sets of GL 521 and GL 806 to exhibit only marginal evidence of velocity variations.

c) Limits to Companion Masses

To relate companion mass to the orbital parameters one may use the mass function:

$$\frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{P}{2\pi G}(1 - e^2)^{3/2} K_1^3 , \qquad (4)$$

where M_1 and M_2 are the masses of primary and secondary, and P, e, and K_1 are the period, eccentricity, and velocity semiamplitude, respectively. From equation (4), one may estimate the companion masses for the three original detections of velocity variations discussed above. The phased velocity sets, such as that in Figure 2, permit rough estimates of K_1 and e, giving, GL 380: ($K_1 = 0.4$ km s^{-1}, $e = 0$); GL 521: ($K_1 = 0.6$ km s^{-1}, $e = 0.6$); GL 806: ($K_1 = 0.55$ km s^{-1}, $e = 0.2$). If we assume a value for sin i of $\pi/4$, and adopt typical masses for the primaries ($M = 0.35\ M_\odot$ at M0, and $M = 0.31\ M_\odot$ at M3), the inferred companion masses are 0.005 $M_\odot$, 0.012 $M_\odot$, and 0.011 $M_\odot$ for Gliese 380, 521, and 806, respectively. We consider these mass estimates to represent only rough guidelines for use in future corroborative efforts. We emphasize that not only are the existences of these variations suspect, but the periods used here, taken from the peaks of the periodogram analysis, are highly susceptible to aliasing. However, this exercise does indicate that companions with masses of about 0.01 $M_\odot$ lie near the detectability limit.

The actual minimum companion mass that is detectable for the typical star in this project may be derived from equation (4) by determining the threshold value for K_1 that is required for a detection. We estimated this K_1 threshold by generating artificial velocity curves containing sinusoidal variations with Gaussian errors of 230 m s^{-1}. The artificial velocity curves spanned a wide range of assumed periods, companion masses, and orbital phases, and were spaced in time similarly to our actual observations. For each of thousands of these artificial velocity curves, we computed the statistical significance of variation with both the F-test and the Scargle periodogram analyses. This Monte Carlo approach is especially useful for cases in which the assumed orbital period is comparable to or greater than the duration of observations, *viz.*, 4 yr. A given pair of input parameters, namely, companion mass and period, were deemed "detectable" if 95% of the trials yielded a detection at the 95% confidence level via F-test or periodogram analysis.

Figure 3 shows the resulting detectability curve as a function of companion mass and orbital period for a typical star in the survey having mass of 0.35 $M_\odot$ and an average orbital inclination, $\langle \sin i \rangle = \pi/4$. Circular orbits have been assumed here.

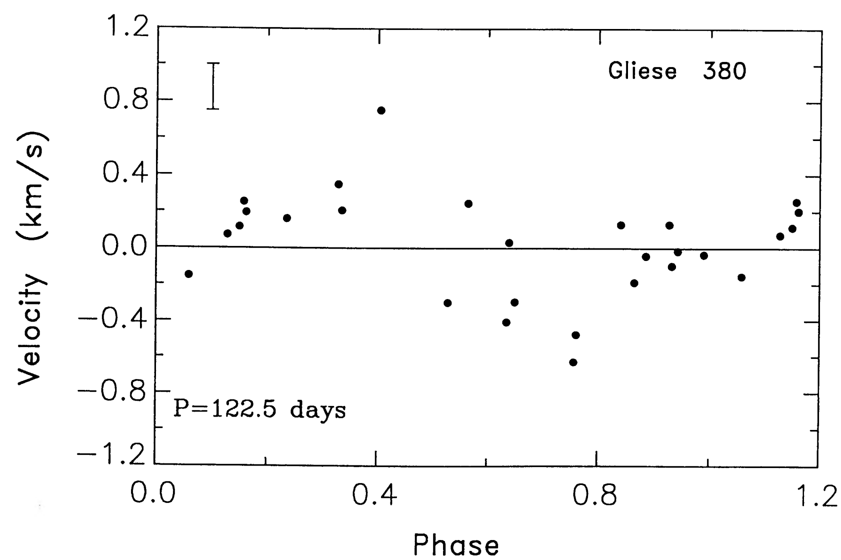

FIG. 2.—The phased measured velocities for Gliese 380. The period of $122\overset{d}{.}5$ is derived from the Scargle-periodogram analysis and the reality of the variation has a false-alarm probability of less than 1%. However, we regard this currently as a marginal detection, given the low ratio of velocity signal to 1 σ error (*upper left*). If substantiated, the minimum mass of the companion is 0.005 $M_\odot$.

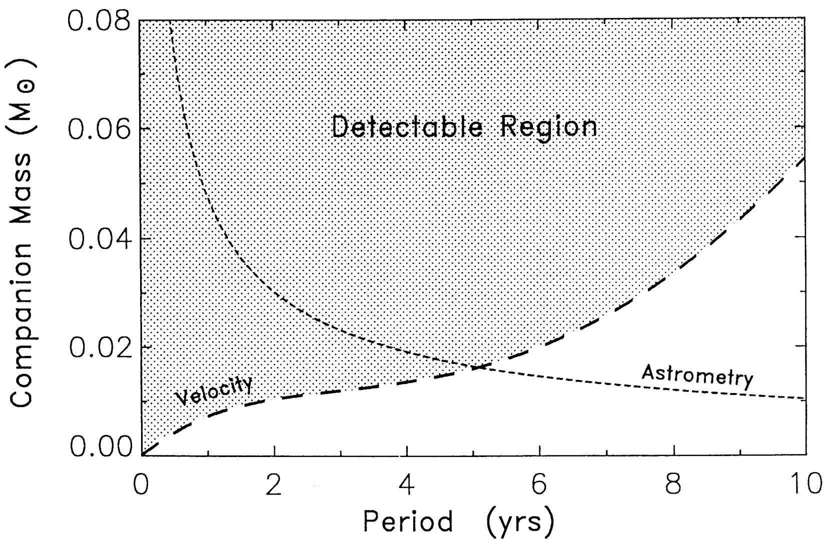

FIG. 3.—Detectability of substellar companions by radial velocity and astrometric measurements in two-parameter space of companion mass and orbital period. The dotted region shows detectability by velocities and the region above the line labeled "astrometry" represents detectability by astrometric perturbations. The velocity curve is constructed assuming that sin i has its average value of $\pi/4$ and is based on a 95% confidence level for detection of periodicity. The astrometry curve assumes that perturbations of 0".02 would have been detected.

For orbital periods less than 4 yr, the minimum detectable companion mass, $M_{\rm min}$, is found to be

$$M_{\rm min} = 0.007 \frac{P_{\rm yr}^{1/3}}{\sin i} (M_\odot) , \quad (5)$$

where the dependence on P and sin i follows from equation (4) and the coefficient of 0.007 is derived from the Monte Carlo tests.

As expected, the Scargle periodogram analysis yields a lower detectable companion mass owing to its greater ability to detect buried periodicity, for a given standard deviation in the velocities. For example, for periods of 2 years the periodogram analysis suggests that companion masses of 0.0085 $M_\odot$/sin i are detectable at the 95% confidence level, while the F-test gives 0.010 $M_\odot$/sin i. The corresponding detectable thresholds for K_1 are 470 and 550 m s^{-1}, respectively, for a 2 year period. In essence, this suggests that we could detect velocity periodicties having amplitude of about twice our measurement uncertainty of 230 m s^{-1}. For orbital periods greater than 4 yr, Figure 3 shows that the present velocity data become progressively less sensitive to companions both because the velocity perturbation diminishes and because less than a full cycle is sampled.

For longer orbital periods, astrometic detections of perturbations become increasingly sensitive, especially for this sample of nearby ($d_{\rm avg} = 5$ pc), low-mass M dwarfs. From Kepler's third law, the minimum detectable companion mass via astrometry is given by

$$M_2 = \left(\frac{M_*}{P}\right)^{2/3} \frac{\alpha_{\rm L}}{\pi_p} , \quad (6)$$

where the masses are in $M_\odot$, the period is in years and the parallax, π_p, is in arcsec. Here, $\alpha_{\rm L}$ represents the minimum angular perturbation detectable in long-term conventional photographic astrometric studies, such as those carried out over decades at the Sproul, US Naval, Allegheny and McCormick Observatories. In such surveys, $\alpha_{\rm L}$ is conservatively about 0".02 (Heintz 1988), viz., about 3 times the typical error in the parallax. In a similar analysis, Campbell, Walker, and Yang (1988) chose $\alpha_L = 0".01$. The astrometric surveys were often designed to measure parallax and proper motion, so that perturbations would be detected only as extraordinarily large residuals.

Figure 3 includes this astrometric detectability curve for the typical star in the present sample, i.e., one having mass 0.35 $M_\odot$ at a distance of 5 pc. One sees that for $P > 4$ yr, astrometry is capable of detecting companions having masses as low as 0.01 $M_\odot$. The duration of astrometric observations for members of the present sample is, of course, not uniform. But owing to their proximity, most have been the subjects of proper motion and parallax studies that lasted for decades and that would have revealed perturbations having periods of comparable length. (Indeed, many of the stars in this survey have been the subjects of the most intense astrometric studies in history, for example, GL 699 = Barnard's Star, and GL 820AB = 61 Cyg). The duration of several decades that is typical of astrometric studies restricts the orbital periods to which they are sensitive to less than about 30 yr.

A review of available astrometric information on all program stars has been carried out at Sproul Observatory. Thanks are due to W. Heintz for kindly providing his latest results on solar neighborhood stars. The astrometry shows that not a single star in our sample exhibits confirmed perturbations at the 0".02 level. Indeed, owing to the proximity of the stars in this sample, such a perturbation would imply a very low mass companion, prompting coverage by the popular press. We note that the stars in our sample were not selected against astrometric perturbations in any way.

An examination of Figure 3 shows that the combination of present radial velocities with past astrometry would have easily produced detections of any substellar companions having masses as low as 0.02 $M_\odot$ with orbital periods less than 30 yr. However, not a single star in our sample of 60 has exhibited such a companion. We note that these two detection techniques are sensitive to spatially orthogonal perturbations, so that no orbital inclination could escape detection. Furthermore, for $2 < P < 8$ yr, the two techniques are nearly redundant; either one is capable of detecting companions of 0.03 $M_\odot$ or more.

IV. DISCUSSION

a) On the Existence of Brown Dwarfs

The absence of brown dwarf companions to the low-mass stars in our sample prompts questions regarding selection effects that may have influenced the result. As described in § II, the stellar sample contains, as a subsample, 80% of all known single *M* dwarfs that are later than dM2, brighter than $V = 10.5$, and have declination greater than $-10°$. Thus, the sample closely represents the metallicities and ages of *all* low mass stars in the solar neighborhood. Of course another effect that inhibits detection of companions is extreme orbital inclination angles ($i \approx 0°$). Note that the detectability curve already includes this by assuming $\sin i = \pi/4$. Orbital inclination affects detectability significantly only for the least massive brown dwarfs ($M < 0.02\ M_\odot$), as implied by the distribution of sin *i* for random orientations. In addition, orbits of near-zero inclination (face-on) are more easily detected by the astrometric technique because the angular perturbations exist in both coordinates on the sky. In short, we are unable to find any effect that would have shielded brown dwarfs from the dynamical detection techniques. Also, unlike photometric searches, this search for brown dwarfs is completely independent of their luminosity. In summary, this survey sampled a representative set of low-mass stars and contains no significant selection effects against detection of brown dwarfs. Therefore, the null result argues strongly that brown dwarf companions, 0.01–0.08 $M_\odot$, are extremely rare within 7 AU of low-mass dwarfs *in general.*

A similar absence of brown dwarfs (down to 0.01 $M_\odot$) around a sample of 16 F, G, and K main-sequence stars has emerged from the precision radial velocity work of Campbell, Walker, and Yang (1988). This stellar sample, though smaller, suggests that brown dwarf companions are rare around solar-type stars as well. Astrometric work on these stars, similar to that on M dwarfs, shows that the dearth of brown dwarf companions extends to orbital periods of 30 yr, i.e., to distances of 10 AU.

In addition, a number of infrared photometric searches for cool companions to nearby stars have been carried out, notably by Probst and O'Connell (1982), Jameson, Sherrington, and Giles (1983), Skrutsie, Forrest, and Shure (1986), McCarthy (1986), and Zuckerman and Becklin (1987*a*). The typical luminosity sensitivity of these searches corresponds to a range of theoretical masses of about 0.04–0.08 $M_\odot$. For example, Skrutsie, Forrest, and Shure (1986) have imaged over 60 nearby stars and could have detected companions greater than 0.04 $M_\odot$ residing 20–70 AU from the primary. Neither this nor the other photometric searches has revealed an unambiguous brown dwarf companion. We emphasize that the photometric searches were sensitive to companions located several arcsec or more from the primary (also less than 1″ in McCarthy's search), corresponding to separations greater than roughly 10 AU from the primary star. *Thus the photometric searches compliment the astrometric and velocity searches, providing detectability primarily for large orbital distances out to 50 AU. Yet, despite hundreds of stars surveyed, no confirmed brown dwarf has been identified.*

Recently, Zuckerman and Becklin (1987*b*) have discovered large infrared excesses around approximately 10% of the target field white dwarfs observed (B. Zuckerman, personal communication). For the published case of G29-38 (Zuckerman and Becklin 1987*b*), the emitting material is shown to lie less than 5 AU from the white dwarf. It would be remarkable if this were actually a brown dwarf, in view of the numerous nondetections of brown dwarfs at similar orbital distances from normal main-sequence stars, discussed above. Further, the giant-branch evolutionary stage of white dwarf primary stars represents a less than hospitable environment, both thermally and perhaps dynamically, for nearby companion brown dwarfs (Livio and Soker 1984). It would be puzzling if brown dwarfs were common near evolved stars while absent around quiescent main-sequence stars. Separations greater than 50 AU, however, would not present such a conflict. Also interesting is the discovery, by direct infrared imaging, of a low-temperature, low-luminosity companion to Gliese 569 by Forrest, Skrutskie, and Shure (1988). Its mass, inferred from models of stars near the H-burning threshold, is sensitive to the assumed age, leaving its status as a brown dwarf unknown. A low-resolution optical spectrum of the companion obtained recently (Marcy and Cohen 1989) is similar to that of a very low mass M dwarf.

Finally, several searches for isolated field brown dwarfs have been carried out. Cutri *et al.* (1985) and Beichman (1987) have searched the *IRAS* Point Source Catalog and the more sensitive Serendipitous Survey enabling detection of massive brown dwarfs ($M > 0.05\ M_\odot$) out to a distance of 3 pc. No confirmed candidates were found. In another search, Boeshaar, Tyson, and Seitzer (1986) obtained extraordinarily deep CCD frames that permitted detection of very red objects as faint as $M_V \approx 19$ out to 400 pc. ($M_v = 16$ corresponds to 0.1 $M_\odot$.) The seven reported frames covered approximately 20 pc^3 and revealed no brown dwarfs. Also relevant are the several attempts to measure the luminosity function, and hence the mass function near the hydrogen-burning cutoff (see Dahn, Liebert, and Harrington 1986; Gilmore, Reid, and Hewitt 1985; Hawkins 1986; and Boeshaar, Tyson, and Seitzer 1986). Unfortunately, there is no agreement as to the sign of the slope of the luminosity function near $M = 0.1\ M_\odot$, and the additional uncertainty in the mass-luminosity relation certainly prevents a meaningful extrapolation to substellar masses. In any case, field brown dwarfs of low mass would not have been detected at all by these photometric searches, and thus their space density remains poorly constrained. The supposed lack of significant dynamical perturbations of the solar system during its lifetime (Morris and O'Neill 1988) implies only that the density of low-mass brown dwarfs ($M < 0.03\ M_\odot$) is less than a few hundred per pc^3.

b) Implications for the Local Missing Mass

Previous nondetections of brown dwarfs by photometric techniques have been difficult to interpret because a mass-luminosity relation (and, often, a bolometric correction) was required to translate the nondetections in terms of mass. Thus, the nature of the local missing mass, amounting to perhaps 0.1 $M_\odot$ pc^{-3} (e.g., Bahcall 1984), has remained explainable by brown dwarfs. However, the dynamical nondetections of brown dwarfs reported here provide some new information. Since the local star density is about 0.1 pc^{-3} (Gliese, Jahreiss, and Upgren 1987), there would have to be several dark companions per target star, on average, in order for companions to comprise a significant portion of the local missing mass. Such a frequency is clearly ruled out by the non-detections here.

Field brown dwarfs, especially those having low mass, which are both undetectable and most important to the integrated mass, might still comprise much of the local missing mass. For their integrated mass to contribute significantly, their number density per log mass interval must increase toward lower masses at least as fast as $d \log N/d \log M < -2$ (e.g., Liebert and Probst 1987). However, the observed mass function is approximately flat at $M = 0.3\ M_\odot$ (Scalo 1986; Reid 1987), and a flat mass function yields no more than $0.01\ M_\odot\ \mathrm{pc}^{-3}$ in brown dwarfs. Thus an ad hoc mode of star formation that enhances production of low-mass brown dwarfs is required in order to provide the local missing mass. There is currently no proposed mechanism for this required enhanced production of low mass objects. Even if such a mechanism were imagined, it is apparently inoperative in the formation of brown dwarf companions to stars, since such companions definitely are extremely rare at best, while companions with masses greater than $0.08\ M_\odot$ are common (McCarthy *et al.* 1988). The implausibility of this enhanced formation of low mass brown dwarfs, along with the nondetections by *IRAS* and by Boeshaar, Tyson, and Seitzer (1986) suggest, on balance, that field brown dwarfs do not provide $0.1\ M_\odot\ \mathrm{pc}^{-3}$ in the Galactic disk. More information on brown dwarfs can clearly be gained from *IRAS* (Chester *et al.* 1986).

c) *Implications for Star Formation*

The complete absence, in the present sample, of companions having masses below $0.08\ M_\odot$ is surprising given the roughly flat stellar mass distribution of field stars at low stellar masses. More relevant is the mass distribution of the companions to low-mass stars, which may be estimated by a census of M dwarfs in the Gliese catalog (Gliese 1969). About 45% of all M dwarfs have companions with masses between 0.1 and $0.3\ M_\odot$, but only $\sim 15\%$ of these are known to have periods less than 10 yr, yielding an incidence of "short-period" companions of $\sim 7\%$. Certainly 7% is only a lower limit to the true number of such companions because of the lack of a detailed dynamical study of all nearby M dwarfs. If the companion mass function, $dN/d \log M$, were flat, one would expect an equal number of companions in the adjacent bin of equal $\Delta \log M$, i.e., from 0.033 to $0.1\ M_\odot$. In particular, in the present sample of 60 M dwarfs, one would expect 7%, or ~ 4, to have companions with masses between 0.033 and $0.1\ M_\odot$. Instead, only one, Gliese 623, exhibited such a companion, despite the ease with which even lower mass companions would have been detected in this study. It is suggested, therefore, that the companion mass function decreases somewhere near or below $0.1\ M_\odot$.

An examination of known low-mass companions provides a suggestion about the nature of the decrease in the mass function. McCarthy *et al.* (1988) summarize our current knowledge of low-mass companions in their Figure 5, which shows that nine have masses near or just below $0.1\ M_\odot$, but none have confirmed masses below $0.08\ M_\odot$. At the low mass end, both Gliese 234B (=Ross 614B; Liebert and Probst 1987) and Gliese 623B (Marcy and Moore 1989) have well-determined dynamical masses of $0.08 \pm 0.01\ M_\odot$. Perhaps less well-determined are LHS 1047B with a mass of $0.055 \pm 0.03\ M_\odot$ (Ianna, Rohde, and McCarthy 1988) and the barely resolved Gliese 473AB which has recently determined components of mass of 0.057 and $0.051\ M_\odot$ (W. Heintz, personal communication). Many of the nine low-mass companions were detected visually, so they cannot be used alone to assess the companion mass distribution near the substellar limit because of luminosity selection effects. But they do show that companions with masses down to about $0.08\ M_\odot$ definitely exist and are not uncommon.

Below $0.08\ M_\odot$ however, the present dynamical study revealed no companions at all despite their easy detection. (We ignore here the three marginal detections of extremely low mass companions discussed in § III*c*.) Apparently the companion mass distribution drops at approximately $0.08\ M_\odot$. The extreme dearth below $0.08\ M_\odot$ suggests that this mass may represent some characteristic minimum mass for formation of companions. Remarkably, this minimum mass of formation coincides with the theoretically expected threshold mass for stable hydrogen burning (Nelson, Rappaport, and Joss 1986; D'Antona and Mazzitelli 1985). We emphasize that this minimum mass of formation arose from dynamical searches alone and therefore is independent of nuclear processes occurring in the companions.

The possibility of a minimum protostellar mass has been explored hydrodynamically assuming a hierarchical fragmentation mechanism for the formation of the smallest masses (e.g., Boss 1987, and references therein). Boss finds a minimum possible fragment of $0.02\ M_\odot$ and argues that a wide variety of conditions, such as subsequent accretion, turbulence, and magnetic fields, all act to increase the minimum final mass. Clearly it would be desirable (though perhaps not simple) to include some of these physical effects to determine more precisely the minimum mass of fragmentation. It would also be useful to relax some of the assumptions in these calculations, such as that of sinusoidal azimuthal perturbations, which produce nearly equal-mass fragments, or that of a bounded cloud volume which truncates accretion.

Shu and Terebey (1984) regard the minimum-mass question as one of astrophysically limiting the further infall of matter onto the protostar, perhaps by stellar winds (Shu, Adams, and Lizano 1987). The proposed winds would be generated at the onset of deuterium burning which causes interior convection, which in turn permits dynamo processes to occur. The resulting surface magnetic fields would power the wind. Significant deuterium burning is predicted to occur for masses greater than $0.015\ M_\odot$ (Lunine, Hubbard, and Marley 1986), so that for small accretion rates the expected minimum mass would be about $0.015\ M_\odot$. This predicted relationship between the minimum mass that will form and the onset of deuterium burning is reminiscent of the coincidence observed here between the minimum observed companion mass ($0.08\ M_\odot$) and the mass required for onset of H-burning.

One might wonder if this stellar-wind suppression of accretion can be operative at the H-burning stage instead of the deuterium-burning stage. The situation is complicated for a companion because it is born in the environment of the primary which will evolve more quickly. Thus, within the context of the Shu, Adams, and Lizano (1987) hypotheses, the minimum companion mass would be determined by duration of accretion that is dictated by the wind of the primary. This scenario would imply that arbitrarily low companion masses could form, which is not observed. Apparently what is needed is a scenario in which accretion onto the companion must continue until at least $0.08\ M_\odot$ is accumulated.

V. SUMMARY

The multiple precise velocities ($\pm 230\ \mathrm{m\ s^{-1}}$) obtained over a 4 year period for 60 low-mass stars enabled detection of companions with masses as low as $0.01\ M_\odot$, as shown in Figure 3.

Only two single-line spectroscopic binaries were convincingly found. One, GL 570B, exhibits a large velocity amplitude implying a companion of stellar mass, and the other, GL 623, was shown to have a companion at the presumed substellar threshold of 0.08 $M_\odot$. However, none of the other stars showed convincing velocity variations, thus implying that brown dwarf companions with masses as low as 0.01 $M_\odot$ are extremely rare. In addition, long-term astrometric studies of all these stars provides information on angular perturbations due to brown dwarf companions of very low mass. However, none of these stars has shown such astrometric perturbation. *These nondetections, both astrometrically and with velocities, strongly suggest that brown dwarfs do not exist within about 10 AU of any of the program stars.* Since this sample is kinematically unbiased, these nondetections show that brown dwarf companions are rare, at best, around low-mass stars in general

This null result was completely unexpected for a number of reasons. First, a large fraction of M dwarfs have companions of stellar mass ($M > 0.08\ M_\odot$), and it was natural to assume that lower mass companions would form as well. Presumably, the reason no brown dwarf companions had ever been identified was simply that their low luminosity hindered detection. Second, one may extrapolate the mass distribution of known stellar companions (e.g., Abt and Levy 1976) to show that a significant fraction may have substellar companions. Third, the null result was unexpected because claims abound in the literature about detected brown dwarf companions, i.e., Barnard's Star and VB8, and several current candidates, discussed in § IV*a*.

Often de-emphasized, however, are the many searches which have produced no brown dwarf companions. For example, Skrutskie, Forrest, and Shure (1986) found none in a deep infrared imaging search around 60 nearby stars. Their one candidate, GL 569, lies near the substellar limit, but probably not far below it, if at all. In addition, an impressive set of nondetections comes from the precision velocities of F, G, and K stars by Campbell *et al.* in which brown dwarfs with masses as low as 0.01 $M_\odot$ would have been detected. The null result of their *dynamical* search is completely independent of selection effects and, like the present nondetections, leads to the strong conclusion that brown dwarf companions are rare. In addition, hundreds of solar neighborhood stars have been studied astrometrically to determine parallax and proper motion. This work is often not designed explicitly to detect perturbations. However, if brown dwarfs were common, deviations of over 0."02 (3 σ) would abound; yet none has been convincingly detected. The photometric searches have also yielded no convincing brown dwarf companions, though the interpretation of these is weakened by the uncertain mass-luminosity relation.

The dynamical searches do not distinguish between companions that formed as protostars and those that formed by accumulation in the host's protostellar disk. Thus, the nondetections show that the incidence of "planetary" companions that have mass above the detection limit of 10 $M_{\rm Jup}$ is extremely low. From the 60 stars examined here, along with the 15 in Campbell's survey, and those in the astrometric work, the incidence is apparently at most 2%. These null results also show that brown dwarf companions cannot contribute significantly to the local missing mass. Field brown dwarfs may still contribute, but their number density as a function of mass must rise dramatically toward lower masses. Such a rise is definitely not seen in the mass distribution of *companions* to stars. On the contrary, it appears that the mass distribution of companions drops steeply at about 0.08 $M_\odot$, based on all known low-mass companions. The reason for this steep drop in terms of protostellar formation is unknown.

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