Recently Discovered Planetary Systems

Data now available were obtained over a 9-10 yr period.

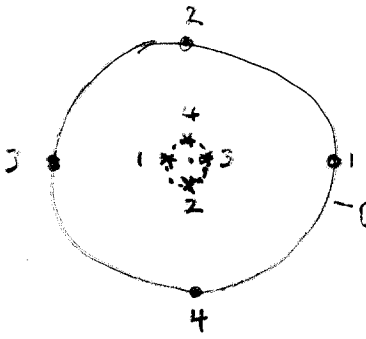
First system reported:
3 planets around a pulsar (1992)

second: HD 114762 1989 (BD or planet?)

3rd: 51 Peg 1995

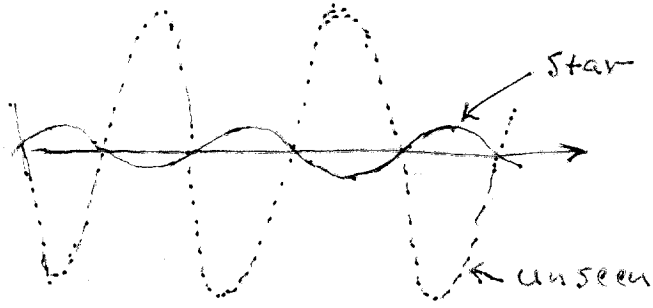
Techniques for finding Planets

Angular Motion on the Sky

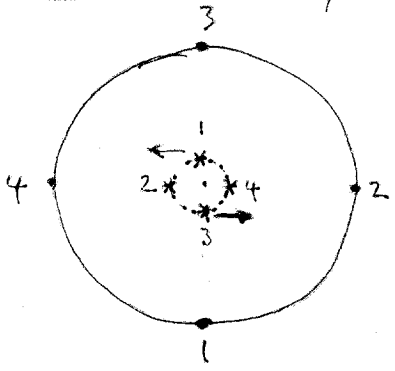


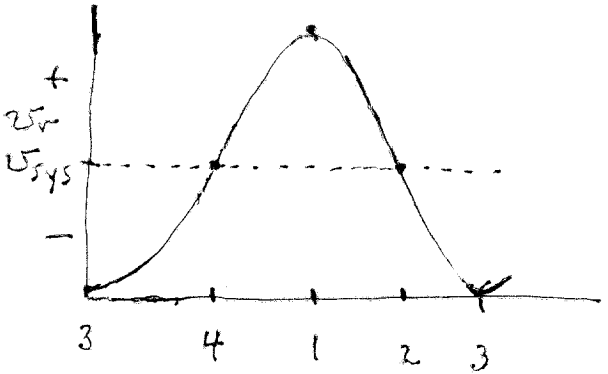
Rest frame of the center of mass.

Relative to the background ✱s



Radial Velocity Shifts (Doppler Effect)





First extra solar planetary system discovered.

Wolszczan + Frail, 1992, Nature, 355, 145.

Millisec Pulsar PSR1257+12

Period $\simeq$ 6.2 msec

Age $\simeq 10^9$ yr

Distance $\simeq$ 500 pc $\simeq$ 1630 ly.

Precise timing measurements indicate at least 2 planets orbiting this rapidly spinning neutron star.

Mass $M_\oplus$	Orbital Radius	Orbital Eccent.	Orbital Period
2.8/sini	0.47 AU	~0	98.2^d
3.4/sini	0.36 AU	~0	66.6^d
~0.015/sini	- - - - - - - - - - - -		?

Residuals $\Rightarrow$ at least one other planet is present in this system.

Pulse period changes of ~ 15 picosec

$\simeq 1.5 \times 10^{-11}$ sec

To the present time about 19 or so stars have been discovered to have LOW-MASS, NON-LUMINOUS companions orbiting about their centers of mass.

~ 9 or so of these are believed to be Planets mass $< 0.02\ M_\odot$ + formed by accretion in a cold disk

+

~ 10 are almost certainly "brown dwarfs" mass $\geq 0.02\ M_\odot$ + formed by fragmentation of parent cloud

None of the "planetary" systems discovered so far are similar to the solar system!

This is not a surprise.

The observational techniques strongly select "massive" companions with small semi-major axes (small orbits).

$$v_r^* \propto M_p / \sqrt{r}$$

Radial reflex velocity

Cochran et al. 1997

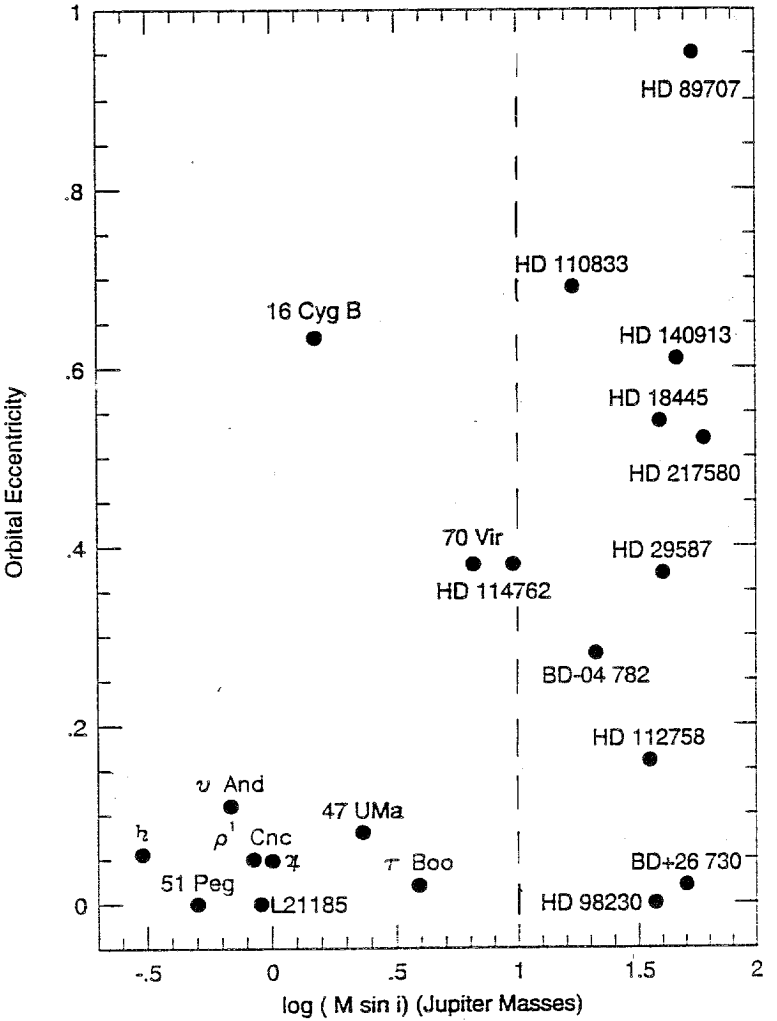


FIG. 3.—Relationship between eccentricity and minimum mass for the substellar companions (both planets and brown dwarfs) found so far.

Five
Four Types of Companions (Planets)

1) 51 Peg Type

51 Peg τ Boo

55 Cnc υ And

$M_p \gtrsim 1 M_{\mathcal{H}}$

Orbital periods ~ several days

Very small orbits!

These planets are believed to have formed in much larger orbits and subsequently perturbed into much smaller ones.

2) Massive Eccentric Objects

HD 114762, 70 Vir

$M_p > 6-10 M_{\mathcal{H}}$

$a \sim 0.4-0.5$ AU

$\epsilon \simeq 0.3-0.4$

3) Pseudo-Jovian Planets

47 UMa, Lalande 21185

$\epsilon \sim 0 \Rightarrow$ almost circular orbits

M_p: up to a few $M_{\mathcal{H}}$

$a > 2$ AU

4) 16 Cyg B

16 Cyg B

$P_{rev} \geq 2\,yr$

$\epsilon \geq 0.6$

$M_p \geq 1 M_4$

5) Planets about pulsars

Latham et al. 1989, Nature, 339, 38

HD 114762

TABLE 1 Orbital solutions

	CfA	CORAVEL	Combined
Period (days)	84.03 ± 0.14	83.91 ± 0.09	84.05 ± 0.08
System velocity, γ (km s^{-1})	49.31 ± 0.03	49.39 ± 0.06	49.35 ± 0.04
Orbital half-amplitude, K (km s^{-1})	0.55 ± 0.04	0.75 ± 0.12	0.57 ± 0.04
Eccentricity, e	0.26 ± 0.07	0.30 ± 0.15	0.25 ± 0.06
Longitude of periastron, ω (°)	237 ± 11	280 ± 16	235 ± 10
Epoch, T (Julian date − 2440000)	5,029 ± 5	5,033 ± 4	5,027 ± 4
Mass function ($10^{-6}\ M_\odot$)	1.3 ± 0.3	3.1 ± 1.5	1.4 ± 0.3
Number of observations	230	50	280
r.m.s. residuals (km s^{-1})	0.42	0.39	0.42

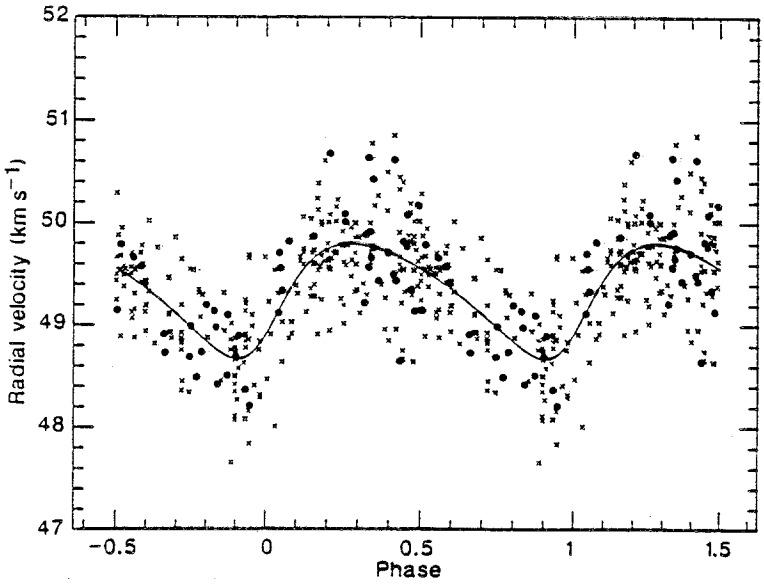


FIG. 2 The orbital solution for the combined data set. The continuous line is the orbital solution with the parameters of Table 1. The CfA velocities are denoted by crosses, the CORAVEL velocities by filled circles.

Marcy et al. 1997, ApJ, 481, 926

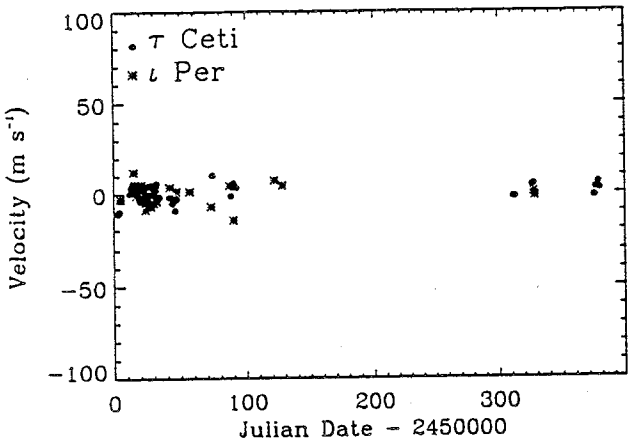


FIG. 1.—Doppler velocities of two stable reference stars. The rms scatter in the velocities of both τ Cet and ι Per is 5 m s^{-1}. These observations were made over the same time span as those for 51 Peg, and illustrate the typical long-term errors of the Doppler measurements.

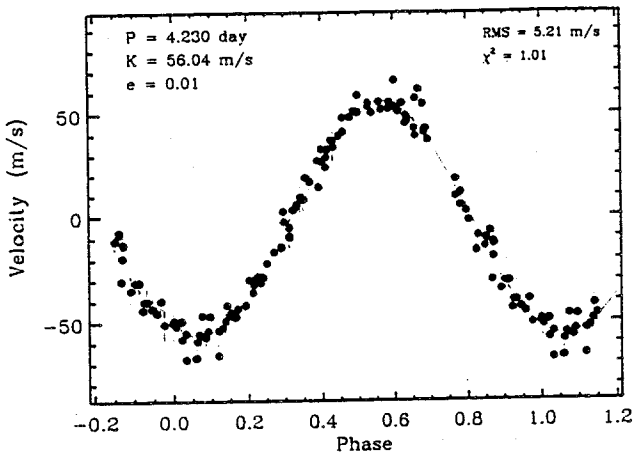


FIG. 3.—51 Peg velocities phased with the Keplerian fit. The variation is sinusoidal with a period of 4.231 ± 0.001 days. Phase stability is precisely maintained during 10 months.

TABLE 3

51 PEG PROPERTIES

Parameter	Value	Source
$T_{\rm eff}$ (K)	5724–5755	Valenti et al. 1995; Edvardsson et al. 1993
M_V	4.56	Perryman et al. 1996 (*Hipparcos*)
$L/L_\odot$	1.24	From $M_V - M_V(\odot)$
Log gravity (cgs)	4.18–4.3	Edvardsson et al. 1993; Valenti et al. 1995
$R/R_\odot$	1.13–1.27	L, $T_{\rm eff}$; log g
Spectral type	G2–3 V	Houk 1995
$R'_{\rm HK}$	−5.037	Noyes et al. 1984
$P_{\rm ROT}$ (days)	29–37	Baliunas et al 1997; Henry et al. 1996
$V \sin i$ (km s^{-1})	1.7–3	Hatzes et al. 1996
[Fe/H]	+0.06 to +0.192	Edvardsson et al. 1993; Valenti et al. 1995
Age (Gyr)	8.5	Edvardsson et al. 1993
Parallax (mas)	65.1 ± 0.8	Perryman et al. 1996

PLANET AROUND 51 PEG

TABLE 2

ORBITAL PARAMETERS OF 51 PEG

Parameter	Mayor & Queloz	This Paper	Uncertainty
P (days)	4.2293	4.2311	0.0005
T_0[a] (JD)	2,449,797.773	2,450,203.947	0.03
e	...	0.012	0.01
ω (deg)	Undefined	Undefined	...
K_1 (m s^{-1})	59	55.9	0.8
$a_1 \sin i$ (m)	3.4×10^6	3.25×10^6	0.05×10^6
f_1 (m) ($M_\odot$)	9.1×10^{-11}	7.64×10^{-11}	...
N	35	110	...
rms $O-C$ (m s^{-1})	13[b]	5.2	...

[a] Time of peak velocity.
[b] After removal of long-term variations.

Butler + Marcy 1996, Ap. J., 464, L153

TABLE 1

47 UMa COMPARED TO THE SUN

Parameter	Sun	47 UMa	Source
$T_{\rm eff}$ (K)	5780	5882	Edvardsson et al. 1993
M_V	4.79	4.40	Cayrel de Strobel et al. 1992
Log gravity (cgs)	4.45	4.31	Blackwell, & Lynas-gray 1994
Spectral type	G2 V	G0 V	Garcia 1989
$R'_{\rm HK}$	−4.937	−5.26	Duncan 1981
$P_{\rm ROT}$ (days)	25.4	16	Soderblom 1985
$V \sin i$ (km s^{-1})	1.8	3	Soderblom 1983
[Fe/H]	0.00	+0.01	Blackwell, & Lynas-Gray 1994
Age (Gyr)	4.6	6.9	Edvardsson et al. 1993
Parallax (arcsec)	...	0.081	Heintz 1993

TABLE 2

ORBITAL PARAMETERS OF 47 UMa

Parameter	Best Fit	Uncertainty
P (day)	1090	15
T_p (JD)	2448497	...
e	0.03	0.06
ω (deg)	275	...
K_1 (m s^{-1})	45.5	3
$a_1 \sin i$ (AU)	0.00454	0.0005
f_1 (m) $(M_\odot)$	1.07×10^{-8}	0.23×10^{-8}
N	34	...
$(O - C)$ (m s^{-1})	10.9	...

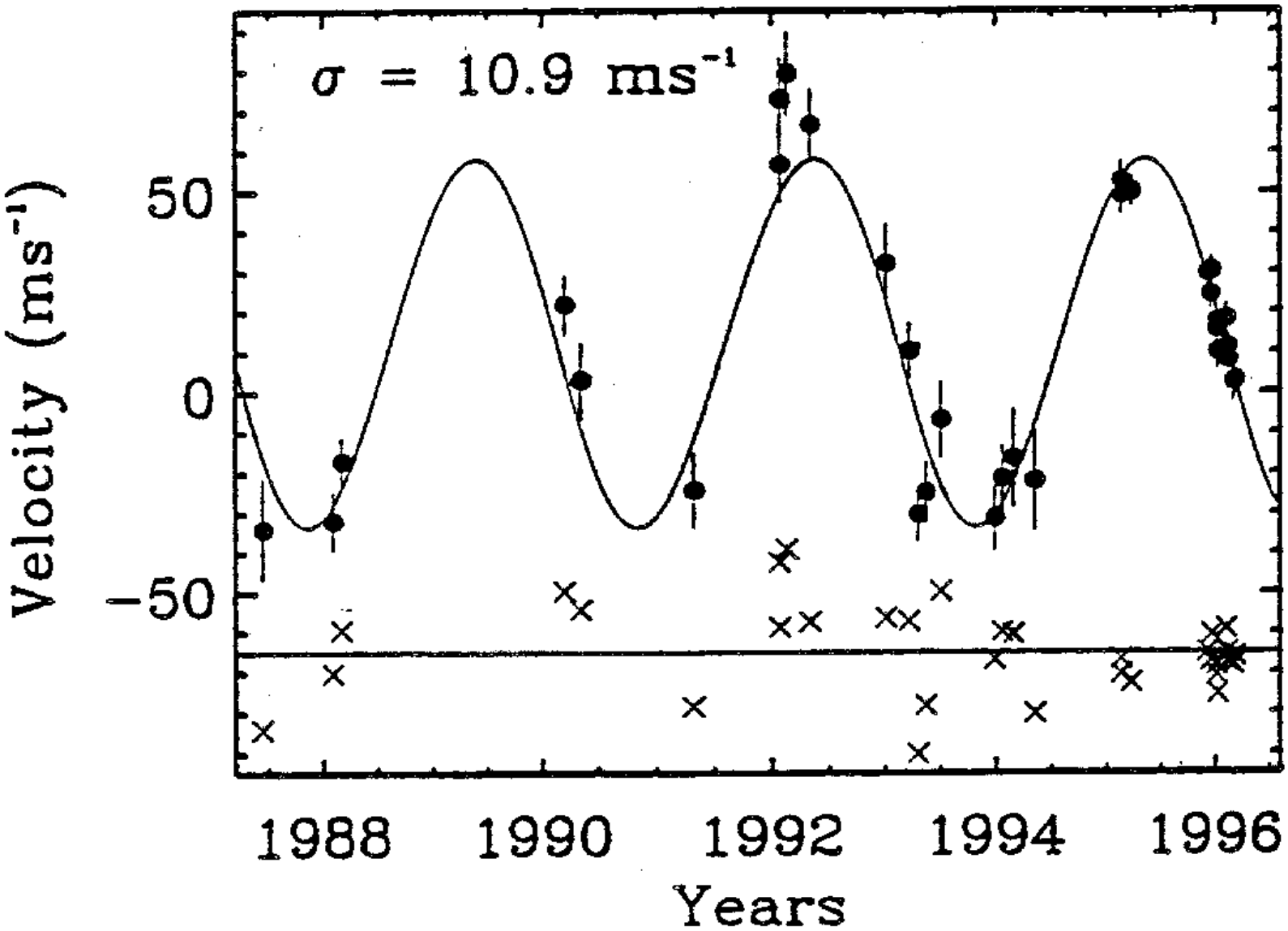


FIG. 3.—Doppler velocities for 47 UMa (G0 V). A total of 34 observations have been made over 8.7 yr, shown as the filled circles. A Keplerian orbit with a period of 1090 days fits the observed velocities, implying a companion mass, $M \sin i = 2.4\ M_J$. The rms of the residuals to the orbital fit is 10.9 m s^{-1}.

Marcy + Butler 1996, Ap. J., 464, L147

TABLE 1

70 VIRGINIS COMPARED TO THE SUN

Parameter	Sun	70 Vir	Reference
$T_{\rm eff}$ (K).....	5780	5488	1
M_V	4.79	5.23	2
log g (cgs).....	4.45	3.80	1
Spectral type.....	G2 V	G4 V	3
$R'_{\rm H.K}$	−4.937	−4.74	4
$P_{\rm rot}$ (days).....	25.4	35	5
$V \sin i$ (km s^{-1})....	1.8	<3	6
[Fe/H].....	0.00	−0.11	1
Age (Gyr).....	4.6	6–10	7
Parallax (arcsec)...	...	0.112	2

REFERENCES—(1) Blackwell & Lynas-Gray 1994; (2) Gliese & Jahreiss 1979; (3) Garcia 1989; (4) Noyes et al. 1984; (5) Soderblom 1985; (6) Strassmeier 1990; (7) Eggen 1989.

TABLE 2

ORBITAL PARAMETERS OF 70 VIRGINIS

Parameter	Best-Fit Value	Uncertainty
P (days).....	116.67	0.01
T_p (JD).....	2448990.403	0.5
e	0.40	0.01
ω (deg)	2.1	2
K_1 (m s^{-1}).....	318	4
$a_1 \sin i$ (AU).....	0.00312	0.00004
$f_1(m)$ ($M_\odot$).....	2.98×10^{-7}	0.2×10^{-7}
N.....	39	...
O − C (m s^{-1}).....	8	...

1996, Ap J., 464, L147

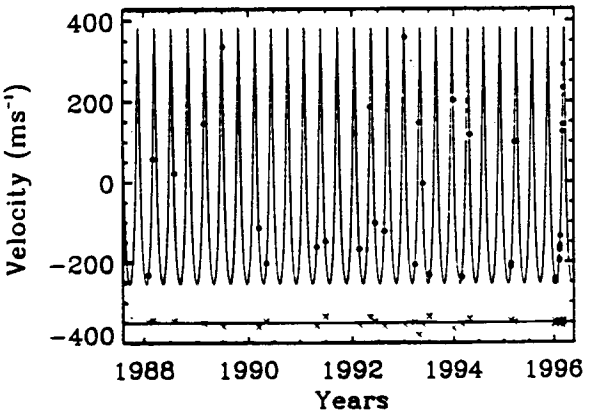


FIG. 2.—Doppler velocities for 70 Vir, showing all 39 observations from 8 yr. The error bars are smaller than the points. An orbital fit yields period $P = 116.7$ days, $e = 0.40$, and $K = 318$ m s^{-1}, for a companion mass of $M_{comp} = 6.6\ M_J$. The residuals to the orbital fit are shown at the bottom, having an rms deviation of 8 m s^{-1}, consistent with the errors of 10 m s^{-1}.

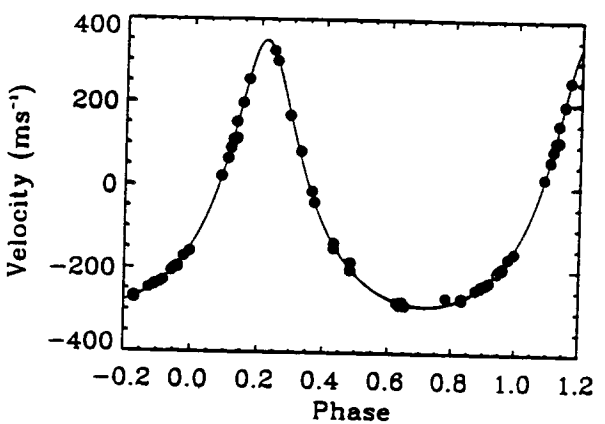


FIG. 3.—Velocities for 70 Vir phased with the orbital fit for $P = 116.67$ days. Error bars are smaller than the points. The derived minimum companion mass is $M_{comp} \sin i = 6.6\ M_J$.

Butler et al. 1997, Ap. J., 474, L115

TABLE 2

ORBITAL PARAMETERS

Parameter	HR 3522	HR 5185	HR 458
P (days)	14.648 (0.0009)	3.3128 (0.0002)	4.611 (0.005)
T_{max} (JD)[a]	2450231.94 (0.8)	2450235.41 (0.2)	2450088.64 (0.3)
e	0.051 (0.013)	0.018 (0.016)	0.109 (0.04)
ω (deg)[b]	41	254	314
K_1 (m s^{-1})	77.1 (0.9)	469 (5)	74.1 (4)
$a_1 \sin i$ (AU)	0.00010	0.00014	0.000032
f_1(m) ($M_\odot$)	7.04×10^{-10}	3.54×10^{-8}	2.18×10^{-10}
N[c]	45	19	18
$O-C$ (m s^{-1})	12.0	13.9	12.1

[a] Time of velocity maximum.
[b] ω is poorly constrained for these circular orbits.
[c] Number of consecutive observations used at end of data string.

υ And
τ Boo
ρ¹ Cnc

TABLE 1

STELLAR CHARACTERISTICS

Parameter	HR 3522	HR 5185	HR 458
T_{eff} (K)	5200[a]	6450[a]	6200[b]
M_V	5.38[c]	3.18[c]	2.86[c]
Log gravity (cgs).....	4.50[a]	4.3[a]	4.2[d]
Spectral type.....	G8V[a]	F7V[a]	F8V[a]
R'_{HK}	−4.97[e]	−4.73[f]	−4.97[e]
P_{ROT} (days).....	44[e]	4[f]	12[e]
$v \sin i$ (km s^{-1})	2.0[g]	14.8[h]	9.2[i]
[Fe/H].....	+0.23[a]	+0.28[a]	+0.09[d]
Age (Gyr).....	5[g]	2[a]	3[d]
Parallax (mas)	76.8 ± 2.4[b]	54.5 ± 4.8[b]	56.8 ± 4.1[b]

[a] Perrin et al. 1977.
[b] van Altena, Lee, & Hoffleit 1995.
[c] From parallax and V magnitude.
[d] Edvardsson et al. 1993.
[e] Soderblom 1985.
[f] Baliunas et al. 1996.
[g] Baliunas et al. 1997.
[h] Gray 1982.
[i] Soderblom 1982.

υ And

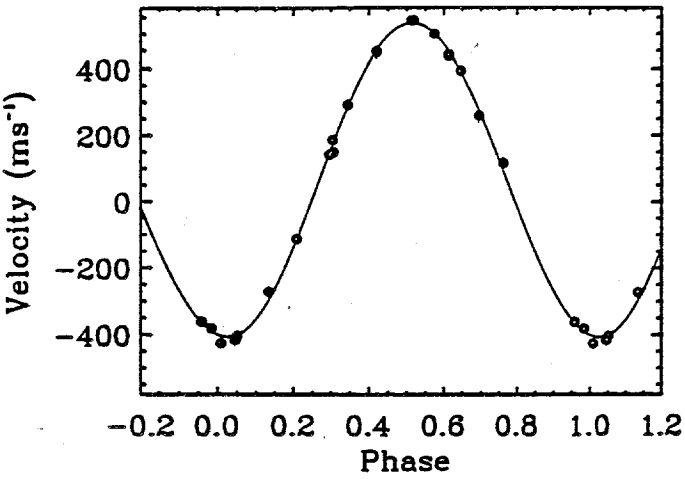


FIG. 3.—Phased Doppler velocities for HR 5185 (τ Boo) for 19 observations obtained since 1994 November. The solid line is the best-fit Keplerian orbit, with $P = 3.3128$ days, $K = 469$ m s^{-1}, and $e = 0.016$, yielding a mass of $m \sin i = 3.9 M_{\rm JUP}$.

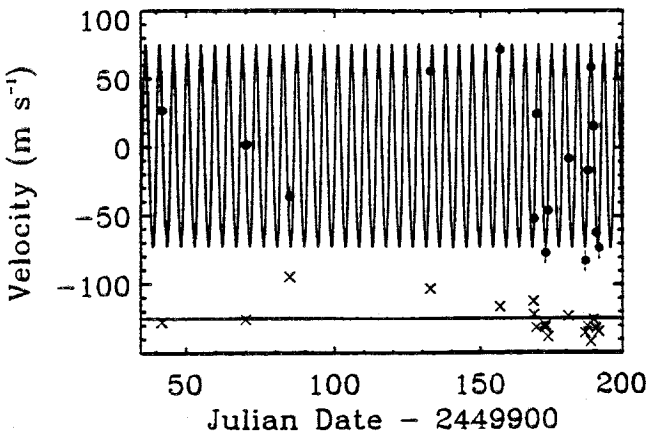


FIG. 4.—Doppler Velocities for HR 458 (υ And) from 1995 August through 1996 January. A Keplerian fit to the measured velocities (*solid line*) yield the following parameters: $P = 4.61$ days, $e = 0.11$, and $K = 74$ m s^{-1}, yielding a companion mass, $m \sin i = 0.68 M_{\rm JUP}$, orbiting with semimajor axis of 0.057 AU.

1997, Ap.J., 483, 457.

TABLE 1

COMPARISON OF PHYSICAL PARAMETERS OF THE SUN WITH 16 CYGNI A AND B

Parameter	Sun	16 Cygni A	16 Cygni B	Reference
Spectral Type	G2 V	G1.5 V	G2.5 V	...
$T_{\rm eff}$ (K).....	5770	5785 ± 25	5760 ± 20	Friel et al. 1993
log g (cgs)	4.44	4.28 ± 0.07	4.35 ± 0.07	Friel et al. 1993
Mass ($M_\odot$)	1.0	1.05 ± 0.05	1.00 ± 0.05	Friel et al. 1993
[Fe/H].....	0.0	$+0.05 \pm 0.06$	$+0.05 \pm 0.06$	Friel et al. 1993
$v \sin i$ (km s^{-1}).....	1.9 ± 0.3	1.6 ± 1.0	2.7 ± 1.0	Soderblom 1982
Rotation Period (days).....	25.38	26.9	29.1	Hale 1994

Companion (planet)

Orbital period ~ 800.8 ± 11.7 days

Orbital reflex vel. ~ 43.9 ± 6.9 m s^{-1}

Orbital eccentricity = 0.634 ± 0.082

Mass $\simeq \frac{1.5}{\sin i} M_4$

Cochran et al. 1997, Ap.J., 483, 457.

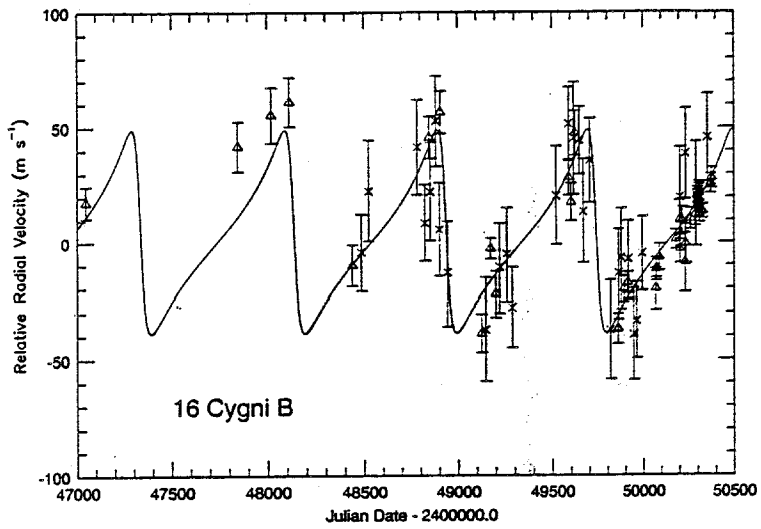


FIG. 1.—Combined Lick and McDonald radial velocities for 16 Cygni B. The triangles are from Lick data and the crosses are from McDonald. The solid line is the radial-velocity curve from the orbital solution.

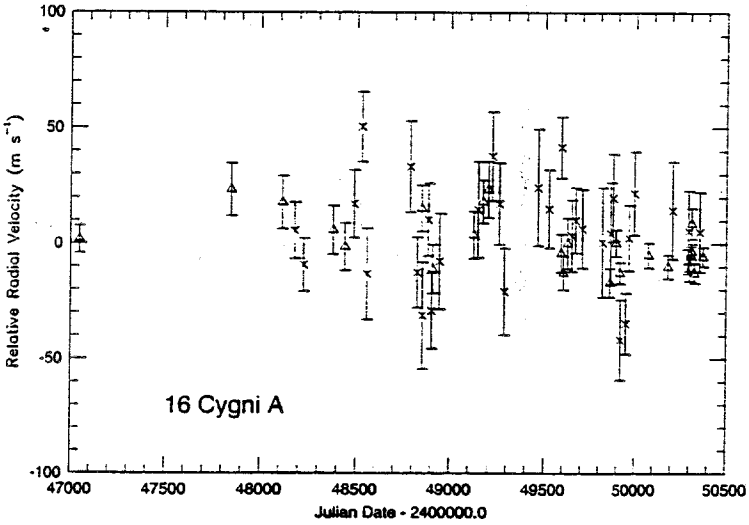


FIG. 2.—Combined Lick and McDonald radial velocities for 16 Cygni A. The symbols are the same as in Fig. 1. No radial-velocity variation is evident in these data.

TABLE 4

COMBINED WEIGHTED ORBITAL SOLUTION FOR 16 CYGNI B

Parameter	Value	Uncertainty
Orbital Period P (days)	800.8	11.7
Velocity Semiamplitude K (m s^{-1}).....	43.9	6.9
Eccentricity e	0.634	0.082
Longitude of Periastron ω (deg).....	83.2	12.7
Periastron Date T_0 (JD)	2448935.3	12.0