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A PLANET ORBITING 47 URSAE MAJORIS[1]

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ABSTRACT

The G0 V star 47 UMa exhibits very low amplitude radial velocity variations having a period of 2.98 yr, a velocity amplitude of $K = 45.5$ m s^{-1}, and small eccentricity. The residuals scatter by 11 m s^{-1} from a Keplerian fit to the 34 velocity measurements obtained during 8 yr. The minimum mass of the unseen companion is $M_2 \sin i = 2.39\ M_J$, and for likely orbital inclinations of 30°–90°, its mass is less than 4.8 M_J. This mass resides in a regime associated with extrasolar giant planets (Burrows and coworkers). Unlike the planet candidates 70 Vir B and 51 Peg B, this companion has an orbital radius (2.1 AU) and eccentricity ($e = 0.03$) reminiscent of giant planets in our solar system. Its effective temperature will be at least 180 K due simply to absorbed stellar radiation, and probably slightly higher due to intrinsic heating from gravitational contraction (Guillot and coworkers). For 47 UMa B to be, instead, an orbiting brown dwarf of mass $M > 40\ M_J$, the inclination would have to be $i < 3\fdg4$, which occurs for only 0.18% of randomly oriented orbits. In any case, this companion is separated from the primary star by $\sim 0\farcs2$, which portends follow-up work by astrometric and direct IR techniques.

Subject headings: stars: low mass, brown dwarfs — stars: planetary systems

1. INTRODUCTION

The observed disks of gas and dust around young solar-type stars have characteristics similar to those required for formation of the planets in our solar system (Beckwith & Sargent 1993; Lissauer 1995). The recent detections of planet-like companions to 51 Peg (Mayor & Queloz 1995; Marcy, Butler, & Williams 1996) and to 70 Vir (Marcy & Butler 1996) provide the first evidence that planet formation may indeed occur commonly around solar-type stars.

However, these first two "planets" exhibit characteristics that are not represented among the nine in our solar system. The planet around 51 Peg has an orbital radius of only 0.051 AU, which is 7 times smaller than the semimajor axis of Mercury. The companion to 70 Vir has a minimum mass of 6.6 M_J and an eccentricity of 0.40, both of which exceed the range of values found among solar system planets. The simple term "planet" may not adequately represent the formation process of 70 Vir b (Marcy & Butler 1996). This planet-like companion may belong to a new class characterized by eccentric orbits $e > 0.2$ and masses 5–15 M_J. The companion to HD 114762 (Latham et al. 1989; Cochran, Hatzes, & Hancock 1991; Hale 1995) may be another member of this prospective eccentric class, as it has $M \sin i = 9\ M_J$ and $e = 0.35$. This class apparently does not extend to higher masses (between 15 and 40 M_J), as they would be easily detected, but have not been found (within 5 AU). At higher masses, "brown dwarf" companions have apparently been found within 5 AU and all exhibit masses greater than 40 M_J (Mayor et al. 1992; Mazeh, Latham, & Stefanik 1996).

Theories of the formation of gas giants predict that the final orbits will be circular, having radii of at least several AU (Boss 1995). These expectations follow from the dissipation that occurs in eccentric orbits within a gaseous disk and from the survival of ice grains beyond 3 AU, where low-equilibrium temperatures are found ($T < 200$ K). The predictions of both circular orbits and large orbital radii are subject to caveats. First, protostellar disks exhibit a range of masses (up to 0.1 $M_\odot$), with some masses exceeding that of the "minimum-mass solar nebula" (Beckwith & Sargent 1993). Such massive disks may have sufficiently high densities of the refractory grains, *inward* of several AU, to permit rapid growth of large rocky cores, leading to gas giants. Even planetary cores that form outside 5 AU may migrate inward (Kary & Lissauer 1995; Lin, Bodenheimer, & Richardson 1996), resulting in gas giants at small orbital radii. Second, significant orbital eccentricities may arise from nonaxisymmetric disk instabilities, which may in fact be driven by a massive protoplanet itself (e.g., Adams, Ruden, & Shu 1989; Artymowicz et al. 1991; Lin & Papaloizou 1993). Thus, the "eccentric planets" around 70 Vir and HD 114762 may stem naturally from massive disks by mechanisms yet to be explored.

Neither 51 Peg B nor 70 Vir B appears to be an obvious analog of planets in our solar system. Here we describe observations of 47 UMa, which exhibits Doppler variations consistent with a planetary companion that has properties reminiscent of solar system planets.

2. THE DOPPLER TECHNIQUE AND STELLAR SAMPLE

In 1987 June we began precise Doppler monitoring of the solar-like star 47 UMa (=HD 95128, HR 4277; $V = 5.05$). As shown in Table 1, 47 UMa and the Sun have similar properties. The effective temperature, absolute visual magnitude, and surface gravity of 47 UMa are all consistent with its being a normal, old disk, G0 V main-sequence star. The relatively low chromospheric index $R'_{HK} = -5.26$ and the modest rotation period of 16 days (Soderblom 1985) suggest that its age is 4–8 Gyr, consistent with the report by Edvardsson et al. (1993). The metallicity of 47 UMa is solar.

This star is one of 120 FGKM main-sequence stars currently monitored in our program. A complete description of the stellar sample and instrumentation is given by Marcy & Butler (1996) and Butler et al. (1996). In brief, we use the Lick

[1] Based on observations obtained at Lick Observatory, which is operated by the University of California.

TABLE 1

47 UMa Compared to the Sun

Parameter	Sun	47 UMa	Source
T_{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'_{HK}	−4.937	−5.26	Duncan 1981
P_{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

Observatory 0.6 m CAT and 3 m Shane telescopes to feed the "Hamilton" coudé echelle spectrograph. Wavelength calibration is accomplished by placing an iodine gas absorption cell in the star beam. The superimposed absorption lines of iodine serve as indelible wavelength markers, and their shapes convey the local spectrometer point-spread function (PSF). The wavelength and PSF parameters are determined by constructing a model of the spectrum that includes the unknown Doppler shift. Relative Doppler errors were 10 m s^{-1} until 1994 November, when improvements in the spectrometer brought the errors to 3 m s^{-1}. For comparison, the reflex motion of the Sun due to Jupiter is 12.5 m s^{-1}, thus rendering gas giants detectable at 5 AU.

For observations made before 1994 November, a velocity zero point is established for each night, based on the observations of 27 stable stars, in order to make nightly velocity corrections (cf. Walker et al. 1995; Campbell, Walker, & Yang 1988). Figure 1 shows these corrections for the 243 nights on which we have carried out observations. For 90% of the nights, the magnitude of the zero-point correction is less than 10 m s^{-1}.

The long-term Doppler precision is empirically determined from the "stable stars" to be ~10 m s^{-1}. This precision is demonstrated in Figure 2, which shows the Doppler measurements for four stars spanning a range of spectral types from G0 to K3. The rms values of the velocity variations for these stars are 7–12 m s^{-1}, representing upper limits to the errors (there may be some small intrinsic variability). A similar set of null results for other stars is shown in Figure 1 of Marcy & Butler (1996). Independently, we estimate an *internal* error for the velocity as judged from the "uncertainty in the mean" of the Doppler measurements of ~500 spectral chunks employed in the analysis. This internal error reflects the agreement of the velocities from the ~500 spectral segments and is determined by the finite signal-to-noise ratio (S/N) of the spectrum as well as by the integrity of the spectral modeling. This internal error is ~10 m s^{-1} for our typical observations, having S/N = 200, in agreement with the external scatter in the velocities for the "null" stars.

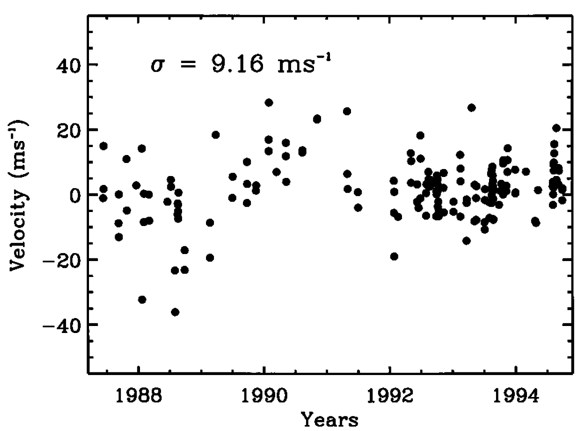

Fig. 1.—Drifts in the velocity zero point prior to 1994 November. The zero point is determined each night based on the average of 27 stable stars. This drift in the velocity zero point is then applied as a nightly correction to all observations made on a given night. Corrections are typically less than 10 m s^{-1}, and the median internal error of the nightly corrections is 4.8 m s^{-1}.

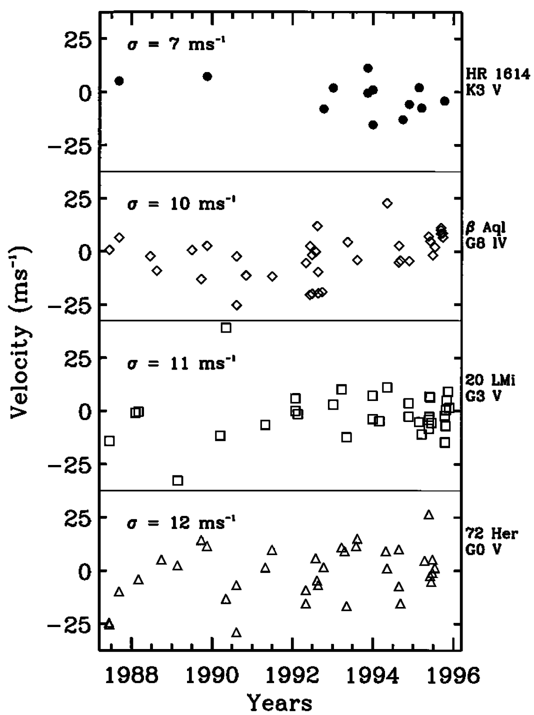

Fig. 2.—Doppler velocities of four stable stars. The stars are identified by name and spectral type along the right edge of the figure. The long-term precision of the iodine technique is 10 m s^{-1} for solar-type stars.

3. VELOCITIES OF 47 URSAE MAJORIS AND AN ORBITAL SOLUTION

A total of 34 observations of 47 UMa have been obtained, spanning 8.7 yr from 1987.5 through 1996.2. The measured Doppler velocities from these observations are shown in Figure 3. The error bars represent the internal error of these observations, ~10 m s^{-1}. The rms of the velocity variations of the 47 UMa observations is 35 m s^{-1}, much greater than the errors. A periodogram analysis finds an extremely strong peak for a period of 3.0 yr, which agrees with an eyeball inspection of Figure 3.

We employ a nonlinear least-squares fitting routine to determine the best-fit Keplerian orbit. Careful inspection of the quality of the fit as a function of the five free orbital parameters reveals two domains giving indistinguishable quality. These two cases are characterized by different eccentricities, namely, e = 0.01 and e = 0.06, both giving a reduced χ^2 of 1.5. The velocity amplitude and period depend only weakly (a few percent difference) on which eccentricity is adopted.

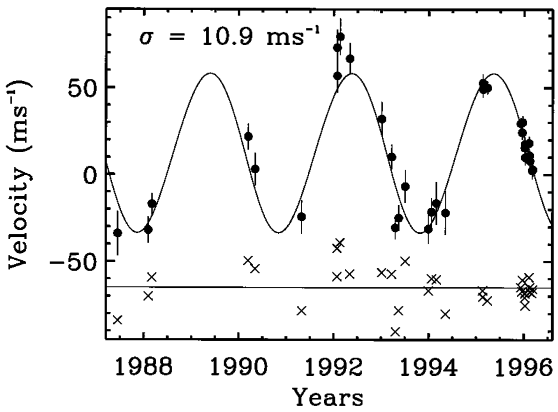

FIG. 3.—Doppler velocities for 47 UMa (G0 V). A total of 34 observations have been made over 8.7 yr, shown as the filled circles. A Keplerian orbit with a period of 1090 days fits the observed velocities, implying a companion mass, $M \sin i = 2.4\ M_J$. The rms of the residuals to the orbital fit is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

Adopting an intermediary eccentricity of 0.03 yields a fit of indistinguishable quality (solid line in Fig. 3). The orbital period is $P = 1090$ days, and the velocity amplitude is $K = 45.5$ m s^{-1}. The rms of the residuals to the orbital fit is 10.9 m s^{-1}. All orbital parameters are listed in Table 2. A Monte Carlo approach yields an uncertainty for all orbital quantities, including the eccentricity of $e = 0.03 \pm 0.06$, consistent with circular.

The period of 2.98 yr and low amplitude of $K = 45.5$ m s^{-1} are consistent with an extremely low mass companion orbiting 47 UMa. In this interpretation, the semimajor axis of the orbit is 2.11 AU. We assume that the primary star has a mass of 1.05 $M_\odot$, based on its spectral classification as G0 V. The derived minimum mass of the companion is

$$M_{\rm comp} \sin i = 2.39\ M_J\ .$$

The uncertainty in $M_{\rm comp} \sin i$ is about 10%, due primarily to the uncertainty in K (45.5 ± 3 m s^{-1}).

4. ALTERNATIVE EXPLANATIONS

There are two alternative explanations that could in principle explain the observed radial velocity signal, namely, spots and pulsation. A large dark stellar spot would cause a net apparent Doppler redshift if it were on the approaching limb of the star, and a blueshift if it were on the receding limb. The period of such a Doppler signal would be the rotation period of the star. However, the estimated rotation period of 47 UMa is 16 days (Soderblom 1985), which is inconsistent with the observed 1090 day periodicity of the velocity variations. Radial pulsation can be ruled out because of the long period. The change in the stellar radius implied by integrating the radial velocity curve shown in Figure 3 is $\pm 4.3\ R_\odot$. Such a radius change would not only imply a dramatic brightness variation of several magnitudes visible to the naked eye but would also require that the radius become negative.

We also considered multiple companions to explain the velocity variations. The periodogram analysis reveals only one strong peak at $P = 1090$ days, with no other peaks having height even 50% as strong. This suggests that only one companion is predominantly responsible for perturbing the primary star. Nonetheless, additional companions that induce perturbations less than 20 m s^{-1} could be responsible for the 2 σ departures in the velocities seen around 1992. Further Doppler measurements are in progress.

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	⋯

5. DISCUSSION

The most viable explanation for the observed velocity variations is that a companion orbits 47 UMa, having a minimum mass of 2.39 M_J. The actual mass remains unknown pending determination of the orbital inclination. We may postulate the existence of a population of brown dwarfs, having masses of 20–80 M_J, which orbit G dwarfs within 5 AU. If so, the lowest mass members (20 M_J) could plausibly reside in nearly face-on orbits to yield the observed low value here for $M_{\rm comp} \sin i$ of 2.39 M_J. The required orbital inclination for a 20 M_J companion is arcsin (2.39/20) = 6°.9. Such extreme inclinations of $i < 6°.9$ occur for 0.75% of randomly oriented orbital planes. Thus, even for a hypothetical brown dwarf mass distribution that peaks at low masses near 20 M_J, the probability is less than 1% that a member would exhibit $M_{\rm comp} \sin i$ of 2.39 M_J.

To estimate the actual mass of 47 UMa B, one may consider a rough range for the inclination of 30°–90°, for which the corresponding companion mass range would be 4.8–2.39 M_J. It is tempting to adopt an "expectation" value of sin i, given by the mathematical mean of its distribution: $\langle \sin i \rangle = \pi/4$. However, such a temptation neglects selection effects. Since 47 UMa B is probably not a member of the hypothetical "brown dwarf continuum" from 20 to 80 M_J, it is likely to be a member of a population characterized by lower masses. The most easily detectable of such members will be those residing in nearly "edge-on" orbits, which would produce the highest velocity amplitudes. Thus, there may be a detection bias toward edge-on orbital inclinations. If so, the actual mass of 47 UMa b may reside near its minimum mass of 2.39 M_J rather than that (3.1 M_J) obtained from adopting the mean of sin i.

Theoretical models of gas giant planets have been computed by Burrows et al. (1995), Saumon et al. (1996), and Guillot et al. (1996). The models contain the relevant interior physics, approximate atmospheric boundary conditions, evolutionary effects (including gravitational contraction), and the absorbed radiation from the host star. The radius of 47 UMa B is estimated from the models to be $R = 1.1\ R_J$, slightly larger than 1 R_J due to radiation from the star (Guillot et al. 1996).

The expected effective temperature is controlled predominantly by equilibrium with the incoming stellar radiation, giving

$$T_{\rm eq} \approx T_*(R_*/2a)^{1/2}(1 - A)^{1/4}\ ,$$

where T_* is the effective temperature of the star, R_* is the stellar radius, a is the distance from the star to the companion,

A is the albedo, taken here to be 0.35 as for Jupiter. This gives an estimate of the planet's temperature,

$$T_{\rm eff} = 180 \text{ K}.$$

The actual effective temperature may be closer to ∼194 K due to internal energy sources (A. Burrows, D. Saumon, & T. Guillot 1996, private communication). The atmosphere may not be a simple temperature-scaled version of Jupiter. The molecular opacities are a sensitive function of temperature and density, and flux redistribution may alter the intensities and emergent spectrum significantly. The predicted effective temperature of 194 K implies that dominant species at optical depth unity would be H_2, He, methane, water, and either ammonia or N_2. Atmospheric clouds and scattering by dust and ice remain as challenges for future models.

One wonders how the companion to 47 UMa should be classified. Since deuterium burning does not take place in objects of 2–3 M_J, 47 UMa B is qualitatively different from the brown dwarfs (Saumon et al. 1996). Indeed, deuterium may portend a method of distinction between planets and brown dwarfs. In addition, Boss (1986) has argued that masses lower than 20 M_J cannot easily form by standard star formation processes. Assistance from grain-grain coagulation may be necessary. The nearly circular orbit suggests formation in a dissipative environment, presumably a disk. For the reasons above, it is tempting to classify 47 UMa B as a giant "planet." We caution that the term "planet" is loaded with implications stemming from the nature and supposed formation of the planets in our solar system. Thus, the firm adoption of the term "planet" for 47 UMa B must await its empirical placement in the context of other low-mass objects orbiting FGK stars. Nonetheless, the orbit and mass of 47 UMa B offer little compelling argument that it differs qualitatively from the gas giants in our solar system.

The presence of a planetary companion to 47 UMa may be verified in the near future by a number of techniques. Clearly, velocity measurements should be carried out by other groups to verify the orbit. Interferometric astrometry should detect a "wobble" of the star. For a parallax of 0″.081 (Heintz 1993) and companion mass of 2.5 M_J, the star resides 0″.00044 from the center of mass, yielding a wobble detectable with future interferometry (Colavita & Shao 1994). Such a measurement would establish the inclination and hence mass of the companion. It is possible that *Hubble Space Telescope* observations can resolve the companion and star that are separated by 0″.17, though the wings of the stellar PSF will likely dominate the companion at all wavelengths, unless the companion is actually stellar. With ground-based instruments, it is possible to detect transits, detectable as a 1% dip in brightness if the orbital inclination is nearly edge on, perhaps favored by the selection effect described above. Spectroscopy in the IR of the unresolved composite system might be able to constrain the nature of the companion.

To date, we have analyzed 60 stars in our sample. We would detect all companions having masses greater than 2 M_J, within 5 AU, except for those in the most extremely inclined orbits. Previously, we reported the detection of an eccentric planetary companion to 70 Vir, with a minimum mass of 6.6 M_J. Including 47 UMa B, two planetary companions have been found in our sample of 60 targets. We estimate the occurrence of giant "planets" having masses greater than 2 M_J to be 3%. The mass distribution of giant planets must have an upper limit at ∼10 M_J, since we have detected none having $M \sin i$ greater than 10 M_J, and HD 114762B may be only slightly more massive (Mazeh et al. 1996; Marcy & Butler 1996). Nonetheless, 47 UMa B seems to have characteristics representative of those found among planets in our solar system. Conversely, the presence of a giant planet orbiting at only 2.1 AU may render terrestrial planets orbiting at ∼1 AU dynamically unstable.

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