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A PLANETARY COMPANION TO 70 VIRGINIS[1]

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ABSTRACT

An extremely low mass companion to the solar-type star 70 Virginis is inferred from the observed periodic Doppler reflex motion of the primary during 8 yr. The minimum mass ($M_2 \sin i$) of 70 Vir "B" is 6.6 Jovian masses (M_J), which falls in the mass range associated with "extrasolar giant planets" (0.3–15 M_J). An orbital fit to the velocities yields a period $P = 116.6$ days, an amplitude $K = 318$ m s^{-1}, and an eccentricity $e = 0.40$. The residuals to the fit scatter by 8 m s^{-1}, consistent with the errors. Thus 70 Vir B and 51 Peg B represent the first planets found outside our solar system. Alternatively, the probability that 70 Vir B is an orbiting brown dwarf of mass $M > 40\ M_J$ is ~1%, requiring an extreme (face-on) orbital inclination of $i < 9°$. With a likely mass of 6.6–9 M_J, 70 Vir B lies in the nebulously defined domain between solar system planets and brown dwarfs. Its effective temperature is computed to be ~90°C. The formation of such giant planets in eccentric orbits is not explained by current theory.

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

1. INTRODUCTION

During the last 15 years, a number of groups have initiated long-term Doppler searches for planets orbiting solar-type stars (Campbell, Walker, & Yang 1988; Walker et al. 1995; Mayor & Queloz 1995; McMillan et al. 1994; Cochran & Hatzes 1994; Brown et al. 1995). These groups have demonstrated long-term precision of 13–30 m s^{-1}. The reflex motion of the Sun due to Jupiter is 12.5 m s^{-1}, thus yielding a detection threshold of ~2 Jovian masses (M_J) at 5 AU. The spectacular detection of the first planetary companion to a solar-type star, 51 Peg, represents the sole discovery to date (Mayor & Queloz 1995; Marcy & Butler 1996). With a mass of 0.5–2 M_J but small orbital radius (0.05 AU), 51 Peg B has challenged theories of the formation of planets (Boss 1995; Lissauer 1995; Wetherill 1994) and has spawned new models (Guillot et al. 1996; Lin, Bodenheimer, & Richardson 1996).

The theory of the interiors and evolution of giant planets from 0.3 to 15 M_J has been computed by Burrows et al. (1995) and Saumon et al. (1996). In this mass range, planets establish nearly identical internal structures and radii (~1 R_J) that are insensitive to their history of formation as a result of degeneracy pressure. Thus, in common semantics, the term "planet" is reserved for objects having masses less than 10–20 M_J. Giant planets may be distinguished from brown dwarfs by various criteria: (1) the presence of rocky cores and an overabundance of heavy elements, (2) the failure to burn deuterium for $M < 12\ M_J$ (Burrows et al. 1995; Saumon et al. 1996), and (3) occurrence in a multiple system of bodies having circular, coplanar orbits (Duquennoy & Mayor 1991).

Conceivably, nature could manufacture objects that satisfy some, but not all, of the these criteria. The simple terms "giant planet" and "brown dwarf" may not adequately specify all of the parameter space for objects in the domain of 0.3–15 M_J. Here we describe Doppler measurements of a solar-type star that exhibits Keplerian motion consistent with the presence of a planetary-mass companion having characteristics intermediate between those expected for planets and brown dwarfs.

2. THE DOPPLER TECHNIQUE AND STELLAR SAMPLE

In 1987 June, we began a Doppler survey of 120 solar-type stars at Lick Observatory, using the high-resolution Hamilton echelle spectrometer (Vogt 1987). We employ both the 3 m Shane and the 0.6 m coudé auxiliary telescope to feed the Hamilton. Wavelength calibration is accomplished by superposing iodine absorption lines directly onto the spectra (Marcy & Butler 1992). Details of the iodine-based Doppler technique are described by Valenti, Butler, & Marcy (1995) and Butler et al. (1996). A 10 cm long iodine absorption cell containing ~0.001 atm of iodine is mounted in front of the spectrograph slit. Starlight passes through the cell, which acts as a transmission filter, imposing thousands of extremely sharp lines on the starlight in the region from 5000 to 6200 Å. The iodine lines provide a fiducial wavelength scale against which to measure Doppler shifts and convey the shape of the instrumental profile of the echelle as a function of wavelength. Relative Doppler errors were initially 10 m s^{-1}, but in 1994 November the Schmidt camera of the echelle spectrometer was upgraded. The intrinsic resolution of the spectrometer ($\lambda/\Delta\lambda$) was increased from 40,000 to 120,000, and as a result, the Doppler precision has improved to 3 m s^{-1} (Butler et al. 1996).

A velocity zero-point correction is established for each night based on the observations of several (three to 10) stable stars. The correction stems from changes in the spectrometer's instrumental profile that remain inadequately treated. This zero-point correction is similar to that employed by Walker et al. (1995). The magnitude of our corrections is typically 10 m s^{-1} (Butler & Marcy 1996). After this standard correction, the short- and long-term Doppler precision is found to be 10 m s^{-1} (or slightly worse, for rapidly rotating or weak-lined stars). This velocity stability is demonstrated in Figure 1, which shows the Doppler measurements for four stars spanning a range of spectral types from G0 through K1. The rms velocity scatter for these stars is 8–11 m s^{-1} over 8 yr, consistent with the errors. Another set of four (different) velocity-stable stars

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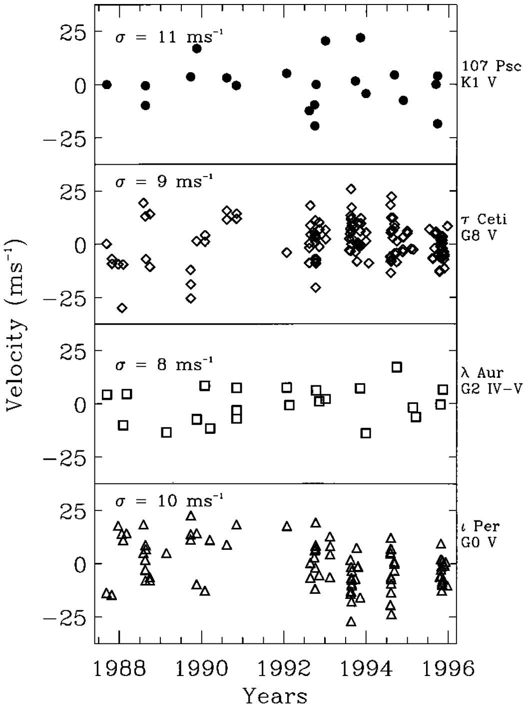

FIG. 1.—Doppler velocities of four nonvarying stars, identified by name and spectral type along the right edge of the figure. From 1987 to 1994 November, the velocity precision was 10 m s^{-1}. Since 1994 November, the precision improved to 3–5 m s^{-1}, depending on the signal-to-noise ratio of the spectrum.

is shown in Butler & Marcy (1996), also exhibiting scatter of ~10 m s^{-1}.

The stellar sample was selected from the brightest F, G, K, and M dwarfs in the Bright Star Catalogue (Hoffleit & Jaschek 1982) and Gliese-Jahreiss catalog (Gliese 1969). We excluded only those stars in stellar binary systems having such small separations that acquisition of individual spectra would be difficult. Thus, for example, 61 Cyg A and B were included but 70 Oph A and B were not. Stars with suspected faint M-dwarf companions ($\Delta m > 5$) or brown dwarf companions were included as interesting cases. Each star was observed two to five times per year. To date, only 60 of the 120 target stars have been analyzed for Doppler measurements.

A few of the stars in our sample show Doppler variations, and most will require additional measurements to elucidate their nature. Of the 60 analyzed stars, 70 Vir (=HR 5072 = HD 117176 = GJ 512.1, G4 V) shows clear periodicity in its velocity. As shown in Table 1, 70 Vir and the Sun have similar properties. Having slightly lower effective temperature and lower luminosity than the Sun, 70 Vir is presumably a main-sequence star of mass $M = 0.92\ M_\odot$ (Blackwell & Lynas-Gray 1994). Its lower surface gravity ($\log g = 3.8$) suggests that it is has just begun to evolve toward subgiant status, with an implied age of 8 Gyr (Eggen 1989). Consistent with its old age, it is chromospherically inactive and is rotating more slowly than the Sun, with $P_{\rm rot} = 35 \pm 7$ days (Soderblom 1985). Its spectrum exhibits no apparent chromospheric emission at Hα nor at the Ca II IR triplet, and the photospheric lines are sharp, consistent with a low value of $V_{\rm rot} \sin i$, less than 3 km s^{-1} (Strassmeier et al. 1990). Its metallicity is 0.1 dex below solar, which is common for field G dwarfs in the solar neighborhood (Cayrel de Strobel et al. 1992).

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.

3. VELOCITIES AND ORBITAL SOLUTION

A total of 39 observations of 70 Vir have been obtained, spanning 8 yr from early 1988 through 1996 March. The measured Doppler velocities from these observations are shown in Figure 2. In contrast with the reference stars of constant velocity in Figure 1, the rms velocity variations of 70 Vir are 187 m s^{-1}, 20 times the errors. The error bars are not visible because they are smaller than the points plotted. A periodogram analysis finds a strong peak at a period of 116.6 days. A Keplerian orbit (*solid curve*) has been found to fit the observed velocities well. The residuals to the orbital fit are shown at the bottom of the figure. The rms deviation of the residuals from the fit is 8 m s^{-1}, consistent with the measurement errors of 10 m s^{-1} (Fig. 1).

Figure 3 shows the 70 Vir velocities phased with the derived period. The best-fit orbital parameters are listed in Table 2, showing a period of 116.67 days, velocity semiamplitude of $K = 318$ m s^{-1}, and eccentricity of 0.40. Assuming that the companion has a mass much less than that of the star, the semimajor axis from Kepler's law is $a = 0.430$ AU. The mass of the companion is given by

$$M_{\rm comp} \sin i = 6.6\, M_{\rm J}\,.$$

The uncertainty in $M_{\rm comp} \sin i$ is ~2%, due primarily to the uncertainty in K.

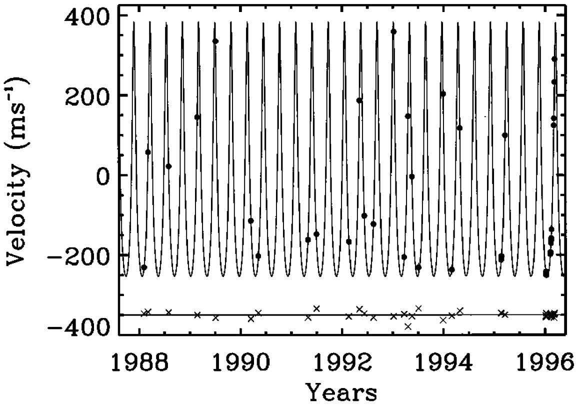

FIG. 2.—Doppler velocities for 70 Vir, showing all 39 observations from 8 yr. The error bars are smaller than the points. An orbital fit yields period $P = 116.7$ days, $e = 0.40$, and $K = 318$ m s^{-1}, for a companion mass of $M_{\rm comp} = 6.6\, M_{\rm J}$. The residuals to the orbital fit are shown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

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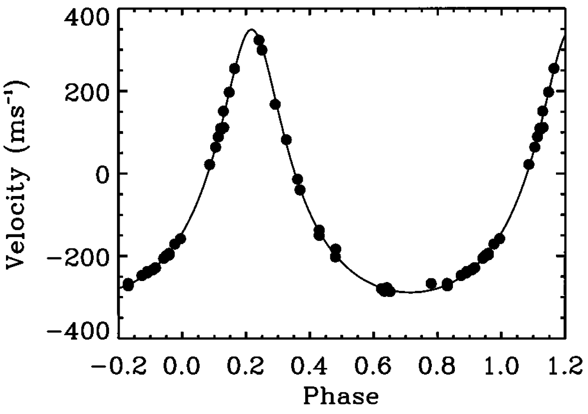

FIG. 3.—Velocities for 70 Vir phased with the orbital fit for $P = 116.67$ days. Error bars are smaller than the points. The derived minimum companion mass is $M_{\rm comp} \sin i = 6.6\ M_{\rm J}$.

4. INCLINATION AND ALTERNATIVE EXPLANATIONS

The velocity curve yields only a value of $M_{\rm comp} \sin i = 6.6\ M_{\rm J}$, with the inclination i left unknown. The companion may be arbitrarily more massive. The companion cannot be more massive than an M3 dwarf, though, since such a companion would exhibit detectable lines in the IR superposed on the G4 V spectrum of the primary. Such IR contamination is not seen (Ginestet et al. 1994), and indeed 70 Vir was deemed an IR spectral standard. Similarly, in broadband *JHK* photometry, 70 Vir appears normal for its spectral type (Selby et al. 1988). The lack of IR contamination of 70 Vir is also evident from the agreement between the value of $T_{\rm eff}$ obtained from *JHK* photometry and that of optical spectroscopy (5488 and 5569 K, respectively, from Blackwell & Lynas-Gray 1994 and Gray & Johanson 1991). Unfortunately, current astrometric measurements of 70 Vir carry precision (50 mas) that is inadequate to constrain the companion (P. A. Ianna 1996, private communication). It remains possible that the velocity variations are caused by either an M3–M10 dwarf or a brown dwarf.

In a random sample of 60 solar-type stars such as ours, 64% are expected to have companions, of which ~40% have masses less than 0.4 $M_\odot$ (dM3), and one-third of those have detectable orbital periods of less than 10 yr (Duquennoy & Mayor 1991). Thus, the frequency of occurrence of short-period companions of spectral types M3–M10 is ~8%, any of which could masquerade as planets if their orbital inclination were extreme (Marcy & Butler 1995). In our sample of 60 stars, about five short-period M-dwarf companions are expected. Indeed, we have already detected three low-mass stellar companions, for HR 6623, HR 753, and HR 2047. Mathematically, the probability that any one of the five expected M-dwarf companions would have the extreme inclination ($i \sim 1\overset{\circ}{.}4$) required to yield $M_{\rm comp} \sin i < 10\ M_{\rm J}$ is $p = 0.0003$ (the fraction of 4π sr subtended by a double cone). Clearly, given five expected M-dwarf companions, the expected number that will masquerade as planets is $5(0.0003) = 0.0015$.

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	···

Alternatively, the companion could be a brown dwarf. We illustrate this possibility by hypothesizing that 70 Vir B is a "typical" brown dwarf having, say, $M > 40\ M_{\rm J}$ that exhibits $M_{\rm comp} \sin i = 6.6\ M_{\rm J}$ as a result of its small (face-on) inclination of $i < 9°$. Such inclination occurs in only 1.3% of randomly oriented orbits. The hypothesis that 70 Vir B actually has $M > 40\ M_{\rm J}$ is clearly improbable. We note that our Doppler measurements would reveal essentially *all* the brown dwarf companions having masses between 20 and 80 $M_{\rm J}$ within 5 AU, and yet no such values of $M_{\rm comp} \sin i$ were seen. Thus our sample of stars contains no large population of "typical" brown dwarfs from which an extraordinary inclination would be expected. For randomly oriented orbits, 68% would be edge-on within 47°, thus yielding a "fiducial" upper mass limit of $M_{\rm comp} < 9\ M_{\rm J}$. A 95% confidence limit yields $M_{\rm comp} < 20\ M_{\rm J}$.

There are two alternative explanations that could account for the observed Doppler periodicity without need of a companion, namely, spots and pulsation. A large stellar spot would cause an apparent net Doppler redshift if it were on the approaching limb of the star and a blueshift if on the receding limb. The period of such a Doppler signal would be the rotation period of the star. The rotation period of 70 Vir of ~35 days is inconsistent with the 117 day Doppler periodicity. Pulsations can also be ruled out because the change in radius implied by integrating the radial velocity curve shown in Figure 3 is 0.7 $R_\odot$, which would produce dramatic changes in luminosity, ruled out by naked-eye photometry.

5. DISCUSSION

The velocity curve of 70 Vir implies a companion of mass between 6.6 and 9 $M_{\rm J}$ in a 117 day orbit, having an eccentricity of $e = 0.40$, with semimajor axis $a = 0.43$ AU. The equilibrium effective temperature computed from Guillot et al. (1996) is

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

where T_* is the effective temperature of the star, R_* is the stellar radius, a is the distance to the companion, and A is the albedo, taken here to be 0.35 as for Jupiter. This yields an estimate of the planet's temperature: $T_{\rm eff} = 355$ K. A more detailed estimate of $T_{\rm eff}$ that includes the redistribution of internal heat, the variation of absorbed stellar radiation due to the orbital eccentricity, and the stored heat capacity yields

$$T_{\rm eff} = 360\ {\rm K}$$

(A. Burrows 1996, private communication). Models that include internal and external heat sources yield a radius for 70 Vir B of $R = 1.05\ R_{\rm J}$ (Burrows et al. 1995; Saumon et al. 1996; Guillot et al. 1996).

At such a temperature, the atmosphere may harbor complex chemistry, including the formation of organic molecules and the condensation of oxides, silicates, and water. One expects a series of cloud layers containing condensates dictated by the relationship between atmospheric pressure and temperature and by the Clausius-Clapeyron equation (Lewis 1995, p. 146). Speculatively, any massive satellites might cradle interesting surface chemistry.

The 70 Vir system is remarkably similar to that of HD 114762, which has $M_{\rm comp}$ sin $i = 9\ M_{\rm J}$, $P = 84$ days, and $e = 0.34$ (Latham et al. 1989; Cochran, Hatzes, & Hancock 1991; Mazeh, Latham, & Stefanik 1996). To estimate sin i, Cochran et al. (1991) placed an upper limit of 1 km s^{-1} on the V sin i rotational velocity for HD 114762. Based on Soderblom's (1985) result that the mean V sin i for F9 V stars is 5 km s^{-1}, Cochran et al. noted that HD 114762 may be oriented nearly pole-on. Assuming coincident equatorial and orbital planes, the small value of sin i implies that the mass of the companion could be near the hydrogen-burning limit (80 $M_{\rm J}$). Cochran et al. noted some uncertainties associated with this argument. Soderblom's relationship between spectral type and rotational velocity has a scatter of 4 km s^{-1}, so the actual equatorial velocity of a given F9 dwarf could be as low as 1 km s^{-1}. Indeed, HD 114762 is an old halo star and has likely spun down more than the typical star (age 2 Gyr) in Soderblom's sample. HD 114762 is also metal-poor, implying an actual mass less than that normally associated with F9 V and thus suggesting a lower expected equatorial velocity (Carney et al. 1994). Given all these uncertainties in the true rotation rate (which favor a less pole-on aspect), the orbital inclination seems unconstrained. Plausibly, the actual companion mass is only $\sim 4/\pi$ greater than its minimum mass of 9 $M_{\rm J}$. If so, the companions to HD 114762 and to 70 Vir have similar eccentricities and semimajor axes and have masses between 6.6 and $\sim$12 $M_{\rm J}$.

At 6.6–9.0 $M_{\rm J}$, 70 Vir B lies in the semantically nebulous gray area between planets and brown dwarfs. Brown dwarfs are thought to differ from planets in that they form by gravitational collapse (as do stars) while planets are built up by dust accretion in the disk of a protostar, followed by hydrodynamic acquisition of gas (Boss 1986; Lissauer 1995). Physically, giant planets supposedly differ from brown dwarfs in that they have a rocky core of $\sim$10 Earth masses. There is currently no observational means of determining the core composition of substellar objects, but the energy generation from deuterium burning in brown dwarfs may be inferred (Saumon, Burrows, & Hubbard 1995). Brown dwarfs are often casually defined as having a lowest mass of 10–20 $M_{\rm J}$ and a maximum mass of 80 $M_{\rm J}$. We propose referring to objects of 5–15 $M_{\rm J}$ with $e > 0.2$ as "eccentric planets" to distinguish them from the less massive giant planets, such as Jupiter and Saturn, which reside in nearly circular orbits. Such an empirical class would become useful only if orbital characteristics correlated with planetary mass or stellar characteristics, thereby suggesting a distinction in formation relative to the conventional "giant planets" and "brown dwarfs." Mechanisms that may increase the eccentricities in massive planets are discussed by Artymowicz (1993).

Along with the recently announced discoveries of the planet with $M_{\rm comp}$ sin $i = 0.45\ M_{\rm J}$ orbiting 51 Peg (Mayor & Queloz 1995; Marcy & Butler 1996; Kennelly et al. 1996) and the 3 $M_{\rm J}$ planet orbiting 47 UMa (Butler & Marcy 1996) with a 3 yr period, this discovery suggests that planetary companions exist with a wide variety of masses and orbital radii.

To date, we have analyzed 60 stars in our sample. We would easily have detected 2 $M_{\rm J}$ companions in orbits that had periods of less than 10 yr. The mass distribution of giant planets must have an upper limit at $\sim$10 $M_{\rm J}$, since we have detected none more massive, and HD 114762B may be only slightly more massive. From our two detections out of 60 stars, the occurrence of planets that have $M > 2\ M_{\rm J}$ with orbital periods of less than 10 yr is $\sim 2/60 \approx 3\%$. Similarly, Mayor & Queloz (1995) have observations of $\sim$100 stars, with only a "small number of stars" showing velocity variations. This provisional 3% rate of occurrence of giant planets explains the nondetections by Walker et al. (1995), as they surveyed only 21 stars. They should have found 0.6 planets with $M > 2\ M_{\rm J}$ and indeed found none. Similarly, Cochran et al. (1994), McMillan et al. (1994), and we (Marcy & Butler 1995) have been unsuccessful with small stellar samples.

With three extrasolar giant planets now known, it is too early to determine the statistics of the occurrence, mass function, or distribution of orbital elements of planetary systems in general. However, the unexpectedly short period of 51 Peg B and the sizable eccentricity of 70 Vir B suggest that the diversity in extrasolar planets is greater than expected. The diversity may stem from a range of protostellar disk masses or disk lifetimes (Beckwith & Sargent 1993; Lissauer 1995; Zuckerman, Forveille, & Kastner 1995). Perhaps high disk masses render the ice condensation boundary irrelevant (plenty of dust, with or without ice grains) but also promote viscous angular momentum loss of planetessimals (Kary & Lissauer 1995; Lin et al. 1996). Perhaps underappreciated processes can influence the evolution of disks that have properties substantially different from the standard solar nebula.

Eric Williams, with outstanding care, carried out many of the observations reported here. Jeff Valenti helped construct the Doppler analysis. Chris McCarthy and Alan Irwin supplied the relativistically correct algorithm for correcting Doppler shifts to the solar system barycenter. We acknowledge generous support from NASA (NAGW-3182), the NSF (AST 95-20443), and Sun Microsystems. S. S. Vogt is gratefully acknowledged for refurbishing the echelle spectrometer, with fine-tuning by Tony Misch. We thank Lars Bildsten, Marc Davis, and Walter Herrick for use of their Sun Microsystems SPARC 20 computers, making this work possible. We thank A. Burrows, D. Saumon, T. Guillot, G. Basri, J. Graham, D. Latham, W. D. Cochran, and D. Werthimer for valuable conversations.

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