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ARTICLES

A Jupiter-mass companion to a solar-type star

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The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

FOR more than ten years, several groups have been examining the radial velocities of dozens of stars, in an attempt to identify orbital motions induced by the presence of heavy planetary companions[1-5]. The precision of spectrographs optimized for Doppler studies and currently in use is limited to about 15 m s^{-1}. As the reflex motion of the Sun due to Jupiter is 13 m s^{-1}, all current searches are limited to the detection of objects with at least the mass of Jupiter (M_J). So far, all precise Doppler surveys have failed to detect any jovian planets or brown dwarfs.

Since April 1994 we have monitored the radial velocity of 142 G and K dwarf stars with a precision of 13 m s^{-1}. The stars in our survey are selected for their apparent constant radial velocity (at lower precision) from a larger sample of stars monitored for 15 years[6,7]. After 18 months of measurements, a small number of stars show significant velocity variations. Although most candidates require additional measurements, we report here the discovery of a companion with a minimum mass of 0.5 M_J, orbiting at 0.05 AU around the solar-type star 51 Peg. Constraints originating from the observed rotational velocity of 51 Peg and from its low chromospheric emission give an upper limit of 2 M_J for the mass of the companion. Alternative explanations to the observed radial velocity variation (pulsation or spot rotation) are unlikely.

The very small distance between the companion and 51 Peg is certainly not predicted by current models of giant planet formation[8]. As the temperature of the companion is above 1,300 K, this object seems to be dangerously close to the Jeans thermal evaporation limit. Moreover, non-thermal evaporation effects are known to be dominant[9] over thermal ones. This jovian-mass companion may therefore be the result of the stripping of a very-low-mass brown dwarf.

The short-period orbital motion of 51 Peg also displays a long-period perturbation, which may be the signature of a second low-mass companion orbiting at larger distance.

Discovery of Jupiter-mass companion(s)

Our measurements are made with the new fibre-fed echelle spectrograph ELODIE of the Haute-Provence Observatory, France[10]. This instrument permits measurements of radial velocity with an accuracy of about 13 m s^{-1} of stars up to 9 mag in an exposure time of <30 min. The radial velocity is computed
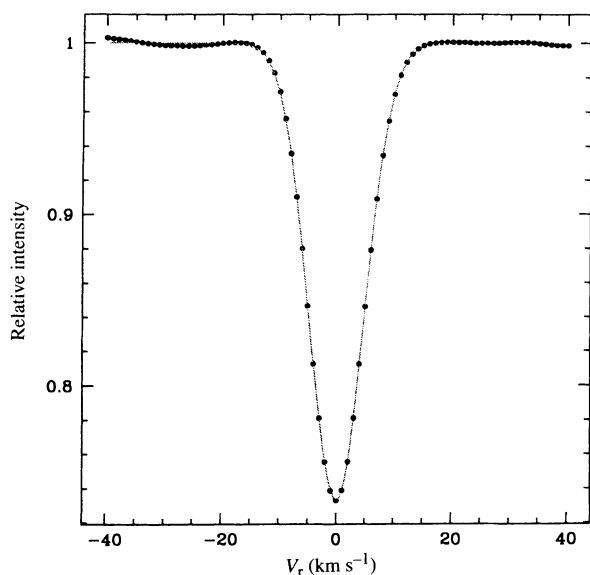
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FIG. 1 Typical cross-correlation function used to measure the radial velocity. This function represents a mean of the spectral lines of the star. The location of the gaussian function fitted (solid line) is a precise measurement of the Doppler shift.

FIG. 3 *a*, ELODIE zero point computed from 87 stars of the sample having more than two measurements and showing no velocity variation. No instrumental zero point drift is detected. *b*, Variation of the γ-velocity of 51 Peg computed from the orbital fits displayed in Fig. 2. Considering the long-term stability of ELODIE this perturbation is probably due to a low-mass companion.

with a cross-correlation technique that concentrates the Doppler information of about 5,000 stellar absorption lines. The position of the cross-correlation function (Fig. 1) is used to compute the radial velocity. The width of the cross-correlation function is related to the star's rotational velocity. The very high radial-velocity accuracy achieved is a result of the scrambling effect of the fibres, as well as monitoring by a calibration lamp of instrumental variations during exposure.

The first observations of 51 Peg started in September 1994. In January 1995 a first 4.23-days orbit was computed and confirmed by intensive observations during eight consecutive nights in July 1995 and eight in September 1995. Nevertheless, a 24 m s^{-1} scatter of the orbital solution was measured. As this is incompatible with the accuracy of ELODIE measurements, we adjusted an orbit to four sets of measurements carried out at four different epochs with only the γ-velocity as a free parameter (see Fig. 2).
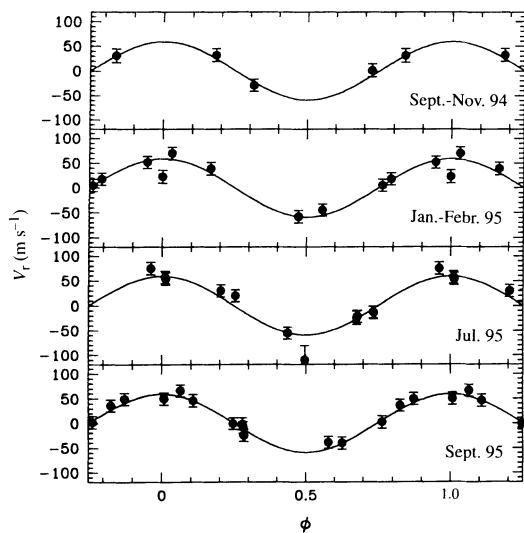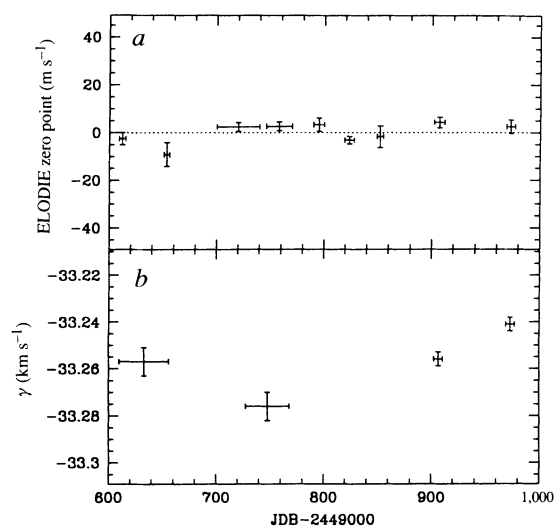
FIG. 2 Orbital motion of 51 Peg at four different epochs corrected from the γ-velocity. The solid line represents the orbital motion fitted on each time span with only the γ-velocity as a free parameter and with the other fixed parameters taken from Table 1.

The γ-velocity in Fig. 3 shows a significant variation that cannot be the result of instrumental drift in the spectrograph. This slow perturbation of the short-period orbit is probably the signature of a second low-mass companion.

The long-period orbit cannot have a large amplitude. The 26 radial velocity measurements made during >12 years with the CORAVEL spectrometer do not reveal any significant variation at a 200 m s^{-1} level. Intensive monitoring of 51 Peg is in progress to confirm this long-period orbit.

In Fig. 4 a short-period circular orbit is fitted to the data after correction of the variation in γ-velocity. Leaving the eccentricity as a free parameter would have given $e = 0.09 \pm 0.06$ with almost the same standard deviation for the r.m.s. residual (13 m s^{-1}). Therefore we consider that a circular orbit cannot be ruled out. At present the eccentricity range is between 0 and about 0.15. Table 1 lists the orbital parameters of the circular-orbit solution.

An orbital period of 4.23 days is rather short, but short-period binaries are not exceptional among solar-type stars. (Five spectroscopic binaries have been found with a period <4 days in a volume-limited sample of 164 G-type dwarfs in the solar vicinity[6].) Although this orbital period is not surprising in binary stars, it is puzzling when we consider the mass obtained for the companion:

$$M_2 \sin i = 0.47 \pm 0.02 \ M_J$$

where i is the (unknown) inclination angle of the orbit.

51 Peg (HR8729, HD217014 or Gliese 882) is a 5.5 mag star, quite similar to the Sun (see Table 2), located 13.7 pc (45 light yr) away. Photometric and spectroscopic analyses indicate a star slightly older than the Sun, with a similar temperature and slight overabundance of heavy elements. The estimated age[11] derived from its luminosity and effective temperature is typical of an old galactic-disk star. The slight overabundance of heavy elements in such an old disk star is noteworthy. But this is certainly not a remarkable peculiarity in view of the observed scatter of stellar metallicities at a given age.

Upper limit for the companion mass

A priori, we could imagine that we are confronted with a normal spectroscopic binary with an orbital plane almost perpendicular to the line of sight. Assuming a random distribution of binary orbital planes, the probability is less than 1% that the companion mass is larger than 4 M_J, and 1/40,000 that it is above the hydr-
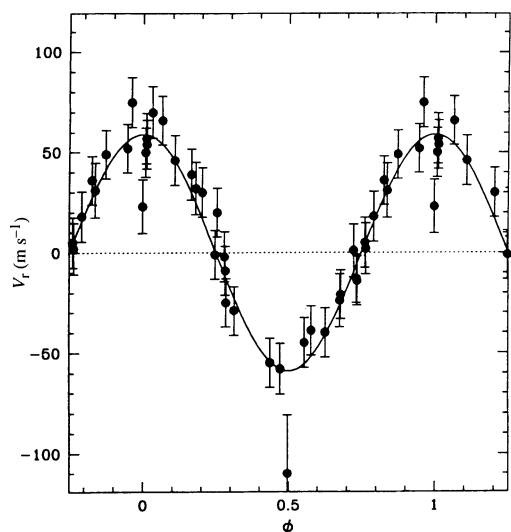
FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the γ-velocity. The solid line represents the orbital motion computed from the parameters of Table 1.

TABLE 2 Physical parameters of 51 Peg compared with those of the Sun

| | Sun | 51 Peg | | |
		Geneva photometry*	Spectroscopy†	Strömgren photometry and spectroscopy[11]
T_{eff} (K)	5,780	5,773	5,724	5,775
log g	4.45	4.32	4.30	4.18
Fe/H	0		0.19	0.06‡
M/H	0	0.20		
M_V	4.79	4.60		
$R/R_{\odot}$	1	1.29		

M/H is the logarithmic ratio of the heavy element abundance compared to the Sun (in dex).
* M. Grenon (personal communication).
† J. Valenti (personal communication).
‡ But other elements such as Na I, Mg I, Al I are overabundant, in excess of 0.20.

ogen-burning limit of 0.08 $M_{\odot}$. Although these probability estimates already imply a low-mass companion for 51 Peg, an even stronger case can be made from considerations of rotational velocity. If we assume that the rotational axis of 51 Peg is aligned with the orbital plane, we can derive $\sin i$ by combining the observed projected rotational velocity ($v \sin i$) with the equatorial velocity $V_{equ} = 2\pi R/P$ ($v \sin i = V_{equ} \cdot \sin i$).

Three independent precise $v \sin i$ determinations of 51 Peg have been made: by line-profile analysis[12], $v \sin i = 1.7 \pm 0.8$ km s^{-1}; by using the cross-correlation function obtained with the CORAVEL spectrometer[13], $v \sin i = 2.1 \pm 0.6$ km s^{-1}; and by using the cross-correlation function obtained with ELODIE, $v \sin i = 2.8 \pm 0.5$ km s^{-1}. The unweighted mean $v \sin i$ is 2.2 ± 0.3 km s^{-1}. The standard error is probably not significant as the determination of very small $v \sin i$ is critically dependent on the supposed macroturbulence in the atmosphere. We accordingly prefer to admit a larger uncertainty: $v \sin i = 2.2 \pm 1$ km s^{-1}.

51 Peg has been actively monitored for variability in its chromospheric activity[14]. Such activity, measured by the re-emission in the core of the Ca II lines, is directly related to stellar rotation via its dynamo-generated magnetic field. A very low level of chromospheric activity is measured for this object. Incidentally, this provides an independent estimate of an age of 10 Gyr (ref. 14), consistent with the other estimates. No rotational modulation has been detected so far from chromospheric emission, but a 30-day period is deduced from the mean chromospheric activity level S-index. A V_{equ} value of 2.2 ± 0.8 km s^{-1} is then com-

puted if a 25% uncertainty in the period determination is assumed.

Using the mean $v \sin i$ and the rotational velocity computed from chromospheric activity, we finally deduce a lower limit of 0.4 for $\sin i$. This corresponds to an upper limit for the mass of the planet of 1.2 M_J. Even if we consider a misalignment as large as 10°, the mass of the companion must still be less than 2 M_J, well below the mass of brown dwarfs.

The 30-day rotation period of 51 Peg is clearly not synchronized with the 4.23-day orbital period of its low-mass companion, despite its very short period. (Spectroscopic binaries with similar periods are all synchronized.) The lack of synchronism on a timescale of 10^{10} yr is a consequence of the q^{-2} ($q = M_2/M_1$) dependence of the synchronization timescale[15]. In principle this can be used to derive an upper limit to the mass of the companion. It does at least rule out the possibility of the presence of a low-mass stellar companion.

Alternative interpretations?

With such a small amplitude of velocity variation and such a short period, pulsation or spot rotation might explain the observations equally well[16,17]. We review these alternative interpretations below and show that they can probably be excluded.

Spot rotation can be dismissed on the basis of the lack of chromospheric activity and the large period derived from the S chromospheric index, which is clearly incompatible with the observed radial-velocity short period. A solar-type star rotating with a period of 4.2 days would have a much stronger chromospheric activity than the currently observed value[14]. Moreover, a period of rotation of 4.2 days for a solar-type star is typical of a very young object (younger than the Pleiades) and certainly not of an old disk star.

Pulsation could easily yield low-amplitude velocity variations similar to the one observed, but would be accompanied by luminosity and colour variations as well as phase-related absorption line asymmetries. The homogeneous photometric survey made by the Hipparcos satellite provides a comprehensive view of the intrinsic variability of stars of different temperatures and luminosities. The spectral type of 51 Peg corresponds to a region of the Hertzsprung–Russell diagram where the stars are the most stable[18].

Among solar-type stars no mechanisms have been identified for the excitation of pulsation modes with periods as long as 4 days. Only modes with very low amplitude ($\ll 1$ m s^{-1}) and periods from minutes to 1 h are detected for the Sun.

Radial velocity variations of a few days and < 100 m s^{-1} amplitude have been reported for a few giant stars[19]. Stars with a similar spectral type and luminosity class are known to be photometric variables[18]. Their observed periods are in

TABLE 1 Orbital parameters of 51 Peg

P	4.2293 ± 0.0011 d
T	$2{,}449{,}797.773 \pm 0.036$
e	0 (fixed)
K_1	0.059 ± 0.003 km s^{-1}
$a_1 \sin i$	$(34 \pm 2) \, 10^5$ m
$f_1(m)$	$(0.91 \pm 0.15) \, 10^{-10} \, M_{\odot}$
N	35 measurements
$(O - C)$	13 m s^{-1}

P, period; T, epoch of the maximum velocity; e, eccentricity; K_1, half-amplitude of the velocity variation; $a_1 \sin i$, where a_1 is the orbital radius; $f_1(m)$, mass function; N, number of observations; $(O - C)$, r.m.s. residual.

agreement with predicted pulsation periods for giant stars with radii $>20 \, R_\odot$. 51 Peg, with its small radius, can definitely not be compared to these stars. These giant stars also pulsate simultaneously in many short-period modes, a feature certainly not present in the one-year span of 51 Peg observations. It is worth noticing that 51 Peg is too cold to be in the δ Scuti instability strip.

G. Burki *et al.* (personal communication) made 116 photometric measurements of 51 Peg and two comparison stars in the summer of 1995 at ESO (la Silla) during 17 almost-consecutive nights. The observed magnitude dispersions for the three stars are virtually identical, respectively $V = 0.0038$ for 51 Peg, and $V = 0.0036$ and 0.0039 for the comparison stars. The fit of a sine curve with a period of 4.2293 days to the photometric data limits the possible amplitude to 0.0019 for V magnitude and 0.0012 for the $[B_2 - V_1]$ Geneva colour index. Despite the high precision of these photometric measurements we cannot completely rule out, with these photometric data alone, the possibility of a very low-amplitude pulsation. In the coming months, stronger constraints can be expected from the numerous Hipparcos photometric data of this star.

Pulsations are known to affect the symmetry of stellar absorption lines. To search for such features we use the cross-correlation technique, as this technique is a powerful tool for measuring mean spectral line characteristics[20]. The difference in radial velocity of the lower and upper parts of the cross-correlation function is an indicator of the line asymmetry. The amplitude of a 4.2-day sine curve adjusted to this index is less than $2 \, \text{m s}^{-1}$. The bisector of the cross-correlation function does not show any significant phase variation.

From all the above arguments, we believe that the only convincing interpretation of the observed velocity variations is that they are due to the orbital motion of a very-low-mass companion.

Jupiter or stripped brown dwarf?

At the moment we certainly do not have an understanding of the formation mechanism of this very-low-mass companion. But we can make some preliminary comments about the importance of evaporation as well as the dynamic evolution of the orbit.

If we compare 51 Peg b with other planets or G-dwarf stellar companions (Fig. 5) it is clear that the mass and the low orbital eccentricity of this object are in the range of heavy planets, but this certainly does not imply that the formation mechanism of this planet was the same as for Jupiter.

Present models for the formation of Jupiter-like planets do not allow the formation of objects with separations as small as 0.05 AU. If ice grains are involved in the formation of giant planets, the minimum semi-major axis for the orbits is about 5 AU (ref. 8), with a minimum period of the order of 10 yr. A Jupiter-type planet probably suffers some orbital decay during its formation by dynamic friction. But it is not clear that this could produce an orbital shrinking from 5 AU to 0.05 AU.

All of the planets in the Solar System heavier than $10^{-6} \, M_\odot$ have almost circular orbits as a result of their origin from a protoplanetary gaseous disk. Because of its close separation, however, the low eccentricity of 51 Peg b is not a proof of similar origin. Tidal dissipation acting on the convective envelope is known[15] to circularize the orbit and produce a secular shrinking of the semi-major axis of binary systems. The characteristic time is essentially proportional to $q^{-1}P^{16/3}$. For stars of the old open cluster M67, orbital circularization is observed for periods lower than 12.5 days (ref. 21). We derive for 51 Peg a circularization time of a few billion years, shorter than the age of the system. The low orbital eccentricity of 51 Peg b could result from the dynamic evolution of the system and not necessarily from its formation conditions.

A Jupiter-sized planet as close as 0.05 AU to 51 Peg should have a rather high temperature of about 1,300 K. To avoid a significant evaporation of a gaseous atmosphere, the escape
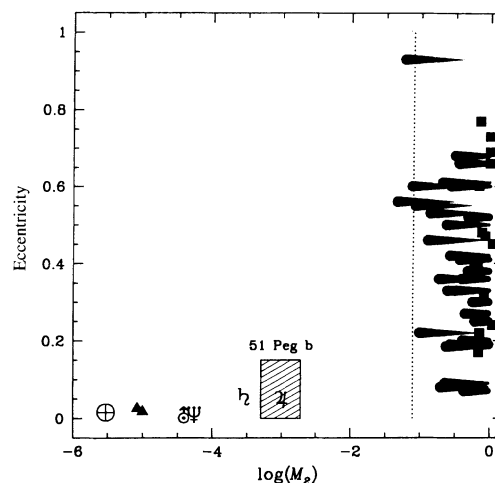

FIG. 5 Orbital eccentricities of planets as well as companion of G-dwarf binaries[8] in the solar vicinity as a function of their mass M_2. The planets of the Solar System are indicated with their usual symbols. The planets orbiting around the pulsar[24,25] PSR B 1257 + 12 are indicated by filled triangles. The uncertainties on the mass of SB1 (single-spectrum spectroscopic binaries), owing to their unknown orbital inclination, are indicated by an elongated line that thins to a sin *i* probability of 99%. SB2s are indicated by filled squares. (Only the stellar orbits not tidally circularized with periods larger than 11 days are indicated.) Note the discontinuity in the orbital eccentricities when planets are binary stars are compared, and the gap in masses between the giant planets and the lighter secondaries of solar-type stars. The dotted line at 0.08 $M_\odot$ indicates the location of the minimum mass for hydrogen burning. The position of 51 Peg b with its uncertainties is indicated by the hatched rectangle.

velocity V_c has to be larger than the thermal velocity V_{th}: $V_c > a V_{th}$. This imposes a minimum mass for a gaseous planet at a given separation:

$$\frac{M_p}{M_J} > \alpha^2 \left(\frac{kT_*}{m}\right)\left(\frac{GM_J}{R_p}\right)^{-1}(1-\gamma)^{1/4}\left(\frac{R_*}{2a}\right)^{1/2}$$

where γ denotes the albedo of the planet, R_p and M_p are its radius and mass, m is the mass of atoms in the planet atmosphere, and R_* and T_* are the radius and effective temperature of the star.

Our lack of knowledge of the detailed structure of the atmosphere of the planet prevents us from making an accurate estimate of α. A first-order estimate of $\alpha \approx 5$–6 is nevertheless made by analogy with planets of the Solar System[22]. We find that with a planetary radius probably increased by a factor of 2–3 owing to the high surface temperature (A. Burrows, personal communication), gaseous planets more massive than 0.6–1.0 M_J are at the borderline for suffering thermal evaporation. Moreover, for the Solar-System planets, non-thermal evaporative processes are known to be more efficient than thermal ones[9]. The atmosphere of 51 Peg b has thus probably been affected by evaporation.

Recent work[23] on the fragmentation of molecular clouds shows that binary stars can be formed essentially as close to each other as desired, especially if the effects of orbital decay are considered. We can thus speculate that 51 Peg b results from a strong evaporation of a very close and low-mass brown dwarf. In such a case 51 Peg b should mostly consist of heavy elements. This model is also not free of difficulties, as we expect that a brown dwarf suffers less evaporation owing to its larger escape velocity.

We are eager to confirm the presence of the long-period companion and to find its orbital elements. If its mass is in the range of a few times that of Jupiter and its orbit is also quasi-circular, 51 Peg could be the first example of an extrasolar planetary system associated with a solar-type star.

The search for extrasolar planets can be amazingly rich in surprises. From a complete planetary system detected around a pulsar[24,25], to the rather unexpected orbital parameters of 51 Peg b, searches begin to reveal the extraordinary diversity of possible planetary formation sites.

Note added in revision: After the announcement of this discovery at a meeting held in Florence, independent confirmations of the 4.2-day period radial-velocity variation were obtained in mid-October by a team at Lick Observatory, as well as by a joint team from the High Altitude Observatory and the Harvard–Smithsonian Center for Astrophysics. We are deeply grateful to G. Marcy, P. Butler, R. Noyes, T. Kennelly and T. Brown for having immediately communicated their results to us. □

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Unusually strong intramolecular magnetic coupling in a chromium hydride cluster

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MOLECULES with large spins, and associated large magnetic moments, are potential building blocks for magnetic materials[1]. To make such molecules, spin-carrying metal ions can be assembled into polynuclear complexes, but the coupling between the spins is usually antiferromagnetic, leading to antiparallel alignment[2]. Magnetic coupling leading to parallel alignment occurs only rarely, and even then is usually too weak for the alignment to persist at ambient temperatures[3–14]. Here we report the synthesis of a tetranuclear chromium hydride cluster with a ground state of non-zero spin (spin quantum number $S = 7/2$), in which the intramolecular magnetic coupling is so strong that the magnetic alignment is not disturbed appreciably even at room temperature. This ground state cannot be explained either by simple parallel or antiparallel alignment of spins, but can be understood in terms of antiparallel alignment of three Cr(III) moments with one Cr(II) moment. These findings indicate that hydride ligands can mediate extremely strong magnetic exchange interactions between metal ions, and that metal hydrides may therefore be promising components for the construction of molecular magnetic materials.

Exposure of chromium(II) hydride $[Cp''_4Cr_4(\mu_3\text{-}H)_4]$ (where Cp'' is η^5-tetramethyl-ethyl-cyclopentadienyl)[15] to hydrogen gas

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at high pressure (60 atm, C_5H_{12} solvent, 25 °C, 5 days) yielded a new compound, tentatively identified as the polyhydride $[Cp''_4Cr_4H_n]$, in 65% isolated yield. The substance was highly paramagnetic; thus its ^1H NMR spectrum (in C_6D_6) exhibited only two very broad and isotropically shifted resonances (chemical shift 9.0 p.p.m., full width at half maximum (FWHM) 570 Hz and −0.9 p.p.m., FWHM 280 Hz) attributable to the substituents of the cyclopentadienyl ligands. No hydride resonances were found. A single-crystal X-ray diffraction study yielded the positions of the heavy atoms ($T = 298$ K, orthorhombic, space group *Pnma*, unit-cell constants $a = 15.447$ (3) Å, $b = 17.242$ (5) Å, $c = 16.221$ (5) Å, $V = 4320.5$ (21) Å^3, $Z = 4$, $d_{calc} = 1.250$ g cm^{-3}, $\mu = 1.012$ mm^{-1}, (where Z is the number of molecules per unit cell, d_{calc} is the calculated density and μ is the linear absorption coefficient) 4,989 reflections collected, 1,657 observed ($F > 5.0\sigma(F)$), $R = 5.40\%$, $R_w = 6.16\%$). Like its precursor, the new cluster consists of an approximately tetrahedral array of four chromium atoms, each of which is bonded to an alkyl-substituted cyclopentadienyl ligand in the familiar η^5-fashion. But in contrast to the tetrahydride, this compound lies on a crystallographic mirror plane, and its Cr–Cr distances (Cr–Cr$_{avg} = 2.765$ Å, (where Cr$_{avg}$ is the average Cr–Cr distance) range 2.759 (3) to 2.767 (2) Å) are significantly longer (Cr–Cr$_{avg} = 2.651$ Å for $[Cp''_4Cr_4(\mu_3\text{-}H)_4]$). The latter observation is consistent with an increase in the formal oxidation state of chromium, as could be brought about by oxidative addition of H_2 to the starting material. The X-ray structure determination revealed several peaks of residual electron density, which might indicate hydride positions, but an unambiguous determination of the number and positions of chromium-bonded hydrogen atoms proved impossible.

Under these circumstances, a neutron-diffraction study was required to unambiguously characterize the new polyhydride. Diffraction data were acquired at the Brookhaven High Flux Beam Reactor on a large single crystal ($3.3 \times 4.3 \times 5.4$ mm). The initial atomic parameters were taken from the X-ray analysis, and the hydrogen atoms were located from successive Fourier-difference maps. The result of the structure determination is shown in Fig. 1 and selected interatomic distances and angles are listed in Table 1 (temperature $T = 20$ K, orthorhombic, space