A giant planet orbiting the extreme horizontal branch star V 391 Pegasi

(Supplementary Information)

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1. Main properties of V 391 Peg

The characteristics of V 391 Peg (summarized in Table 1) are typical of the extreme horizontal branch class of stars that, unlike "normal" horizontal branch stars, have hydrogen envelopes too thin to sustain shell hydrogen fusion. Its progenitor was most likely a star with a mass of $0.8-0.9\,\mathrm{M}_\odot$ that remained more than 10 Gyr on the main sequence (although a larger mass for the progenitor can not be totally excluded¹). During or just after the red giant phase,

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a particularly strong mass loss phenomenon removed almost all the envelope so that the final product is a hot subdwarf B (sdB) star with a very thin ($<0.01\,\mathrm{M}_\odot$) hydrogen envelope^{2,3,4}. The strong mass loss of the sdB progenitors is still an intriguing mystery that could be related to binary interaction¹, in which the presence of planets could play a role⁵. SdB stars have a narrow mass distribution, with an average mass close to $0.5\,\mathrm{M}_\odot$ (at least this is suggested by asteroseismic measurements⁶). In the future, V 391 Peg is expected to bypass the asymptotic giant branch and form a C-O white dwarf with lower than average mass. Only a small fraction of white dwarfs (of the order of 2%) are formed through this evolutionary channel⁷.

Table 1 | Stellar parameters

Apparent visual magnitude, V	14.57 ± 0.02
Effective temperature ^{a} , T_{eff} [K]	$29,300 \pm 500$
Surface gravity ^a , $\log g$ [cgs units]	5.4 ± 0.1
Helium abundance $^a \log(N(He)/N(H))$	-3.0 ± 0.3
Stellar mass^b , M [M $_{\odot}$]	0.50 ± 0.05
Envelope mass ^b , M_{ENV} [M _{\odot}]	< 0.005
Radius, $R(M, g) [R_{\odot}]$	0.23 ± 0.03
Luminosity, $L(T_{eff}, R) [L_{\odot}]$	35 ± 9
Absolute magnitude, $M_V(L, BC^c)$	3.84 ± 0.28
Distance, $d(V, M_V)$ [pc = parsec]	$1,400 \pm 180$
Age^d [Gyr]	$\gtrsim 10$

^aFrom spectroscopy⁸

2. Observations

The observations were carried out using CCD cameras with Johnson B filters (apart from the last run at the NOT, where a larger filter was used) or B-peaked photoelectric photometers without any filter, which have very similar transmission curves⁹. The telescopes used are listed in Table 2. Note that a programme like this one requires a very large number of nights of observation and therefore can be realized only for relatively bright targets using mainly small (1 m class) telescopes, for which it is easier to obtain long and frequent observing runs.

^bSuggested from asteroseismology

^cAssuming BC (bolometric correction) = -2.95 ± 0.02

^dDepending on the (unknown) initial mass

3. Effective temperature of the planet

An estimate of the planet's effective temperature can be obtained from the sdB luminosity and the planet separation, using the thermal balance equation:

$$4 \sigma \, {\rm T_{eff}}^4 = (1 - {\rm A}) \, {\rm E_s} + 4 \, \epsilon_{\rm p}$$

where σ is the Stefan-Boltzmann constant, A is the Bond albedo of the planet, $E_s = L/(4\pi a^2) \simeq 1.6 \times 10^7 \ \rm erg/cm^2/s$ is the incoming flux from the star (equal to about 12 times the solar constant of our Earth) and ϵ_p is an additional energy flux coming from the planet interior. Assuming A = 0.343 (like Jupiter) and $\epsilon_p << E_s$, the effective temperature (T_{eff}) of the planet should be about 470 K, corresponding to a maximum of the black body radiation near 6.2 μ m from Wien's law. Note that even if the internal energy term were significant, T_{eff} would not increase much due to the E^{1/4} dependence.

4. Inclination of the system and rotational splitting

At present we do not have any indication of the inclination i of the V 391 Peg system, but a lower limit can be derived, in principle, from the splitting of the pulsation frequencies caused by stellar rotation. Such rotational splitting should be visible if the star is not pole-on. Then, assuming that the equator of the star is in the orbital plane of the planet (with pulsational and rotational axes aligned), the detection of a rotational splitting would automatically exclude a small inclination and would set an upper limit to the mass of V 391 Peg b. The fact that in our data we do not see any rotational splitting can either be explained by a very low inclination (but this configuration has a very small probability, see discussion in the manuscript) or by the value l = 0 (l being the spherical harmonic index) that was found for the main pulsation frequency from a preliminary mode identification¹⁰. This means that rotational splitting would affect only the other pulsation modes, tentatively identified as l=1 and l=2, having very low amplitudes, so that the secondary rotationally-split frequencies could simply be below our detection limit.

Note that the possibility that the rotation of the sdB star is synchronized with the orbital period (and would not be measurable then) appears unlikely, due to the q^{-2} ($q = M_2/M_1$) dependence of the synchronization time¹¹. Even during the red giant phase, when the synchronization time diminished because of the large stellar radius¹² (up to $\sim 0.7\,\mathrm{AU}$ at the maximum red giant expansion^{13,1}), the probability of synchronization was low. Moreover, after the mass loss terminated, the star should have spun up as it contracted and settled on the extreme horizontal branch.

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Table 2 | Observing log

Epoch	telescopes	# runs	lenght (hr)
1999 Oct*	NOT $2.6~\mathrm{m}^4$	1	0.7
2000 Sep-Oct	multi-site campaign $(7 \text{ sites})^a$	24	77.3
2000 Nov	$CA 2.2 m^4$	4	8.9
$2000 \mathrm{Dec}$	Loi 1.5 m^3	3	6.2
2001 May	SARA 0.9 m^4 , Loi 1.5 m^3	7	8.0
2001 Jun	Loi 1.5 m^3	4	5.3
2001 Jul	NOT 2.6 m^4 , CA 1.2 m^4	9	10.0
2001 Aug	Loi 1.5 m^3	9	48.0
2001 Oct-Nov	Loi 1.5 m^3	4	8.0
$2001 \mathrm{Dec}$	Loi 1.5 m^3	2	3.8
2002 May**	Loi 1.5 m^3	1	0.6
2002 Jul	La Palma $1.0~\mathrm{m}^4$	3	4.2
2002 Aug	$SLN 0.9 \text{ m}^{1}, \text{ Mol } 1.65 \text{ m}^{3}$	5	14.0
2002 Sep	$Mol 1.65 m^3$	2	2.8
2002 Oct-Nov	CA 1.2 m ⁴ , Tenerife 0.8 m ⁴ , Loi 1.5 m ³	9	17.3
2003 May-Jun	Loi 1.5 m^3 , SARA 0.9 m^4	4	4.9
2003 Aug-Sep	WET XCov23 $(7 \text{ sites})^b$	29	55.0
2003 Sep	Loi 1.5 m^3	2	7.8
2004 Jun	Loi 1.5 m^4	7	10.8
2004 Jul-Aug	$Mol 1.65 m^3, Loi 1.5 m^4$	7	24.3
2004 Oct	Loi 1.5 m^4	2	2.7
2005 Jun**	Loi 1.5 m^4	1	1.0
2005 Sep	Mol 1.65 m ³ , SARA 0.9 m ⁴ , Loi 1.5 m ⁴	7	38.6
2005 Nov-Dec	SARA 0.9 m^4 , Loi 1.5 m^4	2	3.8
2006 Jun	Loi 1.5 m^4	2	4.4
2006 Jul	$TNG 3.5 m^4$	5	5.1
2006 Sep	$CA~2.2~m^4$	4	22.0
2006 Nov	SARA 0.9 m^4 , Loi 1.5 m^4 , CA 2.2 m^4	5	16.5
2006 Dec	NOT 2.6 m^4	3	6.1
	TOT	167	418.2

Notes: CA=Calar Alto, Loi=Loiano, SLN=Serra La Nave, Mol=Moletai.

¹ 1 channel photometer (PMT); ² 2 ch. PMT; ³ 3 ch. PMT; ⁴ CCD.

^{*} This run was not considered (too short).

^{**} This run was considered only when data were combined in one data point per season (Figs 2 and 3 of the paper).

 $[^]a$ Multi-site campaign: Mol 1.65 m³, Tenerife 0.8 m³, Loi 1.5 m³, SARA 0.9 m⁴, Beijing 0.85 m³, Fick 0.6 m², Wendelstein 0.8 m⁴.

 $[^]b$ Whole Earth Telescope XCov23: Loi 1.5 m³, Lulin 1.0 m⁴, Piszkesteto 1.0 m⁴, OHP 1.9 m³, Wise 1.0 m⁴, NOT 2.6 m⁴, KPNO 0.4 m⁴ (see http://wet.physics.iastate.edu/ for more details).