# 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 excluded ${ }^{1}$ ). During or just after the red giant phase,
a particularly strong mass loss phenomenon removed almost all the envelope so that the final product is a hot subdwarf $\mathrm{B}(\mathrm{sdB})$ star with a very thin $\left(<0.01 \mathrm{M}_{\odot}\right)$ hydrogen envelope ${ }^{2,3,4}$. The strong mass loss of the sdB progenitors is still an intriguing mystery that could be related to binary interaction ${ }^{1}$, in which the presence of planets could play a role ${ }^{5}$. 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 measurements ${ }^{6}$ ). 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 channel ${ }^{7}$.

Table 1 | Stellar parameters

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

${ }^{a}$ From spectroscopy ${ }^{8}$
${ }^{b}$ Suggested from asteroseismology
${ }^{c}$ Assuming BC (bolometric correction) $=-2.95 \pm 0.02$
${ }^{d}$ Depending on the (unknown) initial mass

## 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 Bpeaked photoelectric photometers without any filter, which have very similar transmission curves ${ }^{9}$. 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.

## 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:

$$
4 \sigma \mathrm{~T}_{\mathrm{eff}}{ }^{4}=(1-\mathrm{A}) \mathrm{E}_{\mathrm{s}}+4 \epsilon_{\mathrm{p}}
$$

where $\sigma$ is the Stefan-Boltzmann constant, A is the Bond albedo of the planet, $\mathrm{E}_{\mathrm{s}}=\mathrm{L} /\left(4 \pi a^{2}\right) \simeq 1.6 \times 10^{7} \mathrm{erg} / \mathrm{cm}^{2} / \mathrm{s}$ is the incoming flux from the star (equal to about 12 times the solar constant of our Earth) and $\epsilon_{\mathrm{p}}$ is an additional energy flux coming from the planet interior. Assuming $\mathrm{A}=0.343$ (like Jupiter) and $\epsilon_{\mathrm{p}} \ll \mathrm{E}_{\mathrm{s}}$, the effective temperature ( $\mathrm{T}_{\text {eff }}$ ) of the planet should be about 470 K , corresponding to a maximum of the black body radiation near $6.2 \mu \mathrm{~m}$ from Wien's law. Note that even if the internal energy term were significant, $\mathrm{T}_{\text {eff }}$ would not increase much due to the $\mathrm{E}^{1 / 4}$ 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 identification ${ }^{10}$. 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 $\mathrm{q}^{-2}\left(\mathrm{q}=\mathrm{M}_{2} / \mathrm{M}_{1}\right)$ dependence of the synchronization time ${ }^{11}$. Even during the red giant phase, when the synchronization time diminished because of the large stellar radius ${ }^{12}$ (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 $2 \mid$ Observing log

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

Notes: CA=Calar Alto, Loi=Loiano, SLN=Serra La Nave, Mol=Moletai.
${ }^{1} 1$ channel photometer (PMT); ${ }^{2} 2 \mathrm{ch} . \mathrm{PMT} ;{ }^{3} 3 \mathrm{ch} . \mathrm{PMT} ;{ }^{4} \mathrm{CCD}$.

* 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 $1.65 \mathrm{~m}^{3}$, Tenerife $0.8 \mathrm{~m}^{3}$, Loi $1.5 \mathrm{~m}^{3}$, SARA $0.9 \mathrm{~m}^{4}$, Beijing $0.85 \mathrm{~m}^{3}$, Fick $0.6 \mathrm{~m}^{2}$, Wendelstein $0.8 \mathrm{~m}^{4}$.
${ }^{b}$ Whole Earth Telescope XCov23: Loi $1.5 \mathrm{~m}^{3}$, Lulin $1.0 \mathrm{~m}^{4}$, Piszkesteto $1.0 \mathrm{~m}^{4}$, OHP $1.9 \mathrm{~m}^{3}$, Wise $1.0 \mathrm{~m}^{4}$, NOT $2.6 \mathrm{~m}^{4}$, KPNO $0.4 \mathrm{~m}^{4}$ (see http://wet.physics.iastate.edu/for more details).

