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CoRoT-9b, a temperate transiting giant planet

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Among the over 400 known[1] exoplanets, the ~ 70 planets that transit their central star stand out, due to the wealth of information that can be gained about both planet and central star. The CoRoT mission[2] has been designed to detect smaller and longer-periodic transiting exoplanets than can be found from ground observations. It has previously detected several short-periodic planets[3], among them the first terrestrial exoplanet[4,5] , Corot-7b. Here we report the discovery of Corot-9b, which orbits with a period of 95.274 days on a low eccentricity of 0.11±0.04 around a solar-like star. Its periastron distance of 0.36 AU is by far the largest of all transiting planets, yielding a photospheric temperature estimated between 250 and 430K. Unlike previously known transiting planets, the present size of CoRoT-9b should not have been affected by tidal heat dissipation processes. The planet is indeed found to be well described by standard evolution models with an inferred interior composition consistent with that of Jupiter and Saturn. Temperate gas-giant planets with low-to-moderate eccentricities constitute the largest group of currently known[1] planets. With Corot-9b being this group's only known transiting planet, and the possibility to perform transit spectroscopy, it

may give rise to a much better understanding of these common planets and open a new domain of lower temperature exoplanet chemistry.

CoRoT observed the CoRoT-9 host star for 145 days starting on 15 April 2008, in the target window E1_0651 of the survey-field LRc02 in the constellation Serpens Cauda. Two transit-events **(Fig. 1)** were detected in CoRoT's three-color photometry; the first one on 16 May 2008. A model fit to the first transit event indicated a Jupiter-sized planet on an equatorial transit (for values, see Table 1). Alerted by this event, two spectra of CoRoT-9 were obtained with SOPHIE[6] on 5 and 25 August 2008, showing a velocity difference of 35±21 m/s between both epochs, compatible with a giant planet.

Observations of a transit on 1 June 2009 with the Wise Observatory 1m (Israel) and the IAC 80cm (Tenerife) telescopes confirmed that the event originated on the target star itself. A false alarm from possible nearby eclipsing binary stars whose light might have spread into CoRoT's large (16" x 21") aperture mask could therefore be excluded[7]. Radial velocity observations **(Fig 2 and supplementary Table 1)** with the HARPS spectrograph[8] spanning from 21 September 2008 to 20 September 2009 verified a Jupiter-mass planet on a moderately eccentric orbit.

In order to assign reliable absolute values to the size and mass of the CoRoT-9b planet, a precise characterization of the planet host star is required. Spectra taken at the Thüringer Landessternwarte and with the ESO VLT/UVES indicated a G3V star of nearly solar metallicity. Its evolutionary age is not strongly constrained, ranging from 0.15 to 8 Gyr. We favour the higher end of the age range, given the quiescent light curve and the absence of chromospheric activity in the spectra. Its rotational velocity of $v \sin i_{rot} < 3.5$ km/s implies (for a rotational inclination $i_{rot} \sim 90°$) a slow rotation period of > 14 days. Depletion of Li has been noted as a feature of planet-hosting stars[9] and indeed its doublet at 6707Å wasn't found in our spectra.

The combination of the light curve analysis, the radial velocity data and the determined stellar parameters allows the derivation of absolute values for the planet's mass, radius and density (Table 1). The planet has a radius quite similar to Jupiter, with $R_p = 1.05 \pm 0.04\ R_{jup}$, but a somewhat lower mass with $M_p = 0.84 \pm 0.07\ M_{jup}$, leading to a density of 0.90 ± 0.13 g/cm^3, or about 68% that of Jupiter.

Tidal heating is expected to play a negligible role in the planet's evolution. The ratio of the rate of energy from tidal circularisation (assuming an initial eccentricity similar to that of Jupiter) to that from insolation[10] is 30x lower for CoRoT-9b than for HD80606b, and at least 1000x lower relative to all other transiting planets. Similarly, we estimate[11] a mass loss rate of about 8×10^6 g/s, which is the lowest one among the known transiting gas giants; escape processes therefore have not affected the planet significantly since its origin. The fact that CoRoT-9b has a much larger periastron distance than any other known transiting exoplanet also yields constraints on its composition that are strong and independent of hypotheses[10,12] on possible missing energy sources and associated radius inflation: An evolutionary model of CoRoT-9b **(Fig. 3)** shows a good match to the observed radius between 0 and 20 Earth masses of heavy elements, comparable to that of giant planets in our solar system[13].

Effective temperatures of Corot-9b have been calculated using a black-body approximation for the host-star emission and a uniform redistribution of absorbed heat energy between the planet's day and night side. Following the planet classification based on temperature regimes by Sudarsky et al.[14], there are two possible outcomes for CoRoT-9b: For one, it may be among class III planets with temperatures > 350K, which have clear atmosphere without cloud-cover and low Bond-albedos of 0.09-0.12. With this albedo, CoRoT-9b's temperatures would range from 380K at apoastron to 430K at periastron. CoRoT-9b may also be among Class II planets, with much lower temperatures (250 - 290 K) due to a significantly higher Bond-albedo of ~0.8 from the condensation of H_2O in the upper troposphere. The strong inverse dependency of the albedo on temperatures[14] near 350K makes a locking into either class II or class III possible. Transits occur not far from periastron, hence temperatures during transit would be only slightly (< 30K) lower than at periastron. Day/night temperature variations are expected to be very small: For one, from its low tidal dissipation we estimate a timescale for rotational slow-down on the order of 100 Gyr; so its rotation should still be close to the unknown, but likely rapid primordial rate. For another, the planet's radiative timescale at the photosphere, which is inversely proportional to the cube of the photospheric temperature[15], should be around 50 times longer than for a standard Hot-Giant planet with a 1500K irradiation temperature.

Fig. 4 shows a diagram of the eccentricity versus the period for all known planets and for all transiting planets. As can be seen, Corot-9b is the first transiting planet among those with longer periods that does not represent a case of extreme eccentricity with associated extreme temperature changes (e.g. HD80806b's temperature is estimated to rise from ~800K to ~1,500K over a six-hour period near periastron[16]). On the contrary, it is the first transiting planet whose general properties coincide with the largest known population of planets, those of longer periods and low-to-moderate eccentricities, but which previously were known only from RV surveys. Our results on Corot-9b show that these planets may be expected to be rather similar to the giants of our Solar System.

CoRoT-9b's period is about 10 times longer than of any other planet discovered through the transit method, which demonstrates the method's potential to find longer-periodic planets. Further observations of such planets will however present new challenges. CoRoT-9b's distance from its host-star of ~0.9 *mas* is too close for imaging, and regardless of its actual Bond-albedo, its relative secondary eclipse depths will be undetectable, being on the ppm level in both visible and the near IR. The most promising aspect of CoRoT-9b is that it will allow for spectroscopy during primary transits, which may lead to the detection of species at moderate temperatures in the visible and infrared, such as CO_2 at 1.25 micron, CH_4 at 0.95 micron, or H_2O at 6 micron.

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End Notes

Supplementary Information Supplementary Table 1 is linked to the online version of the paper at www.nature.com/nature. Data obtained by the CoRoT mission are made available at http://idoc-corot.ias.u-psud.fr/index.jsp.

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Author contributions HJD coordinated the analysis and its interpretation;

PB, SA, JMA, RA, JC, LC, TM, MO, BS contributed to the treatment of the light curve and the detection of the transits in the Corot data;

FB, DQ, CM, GH, MM, CL, FP, AH, WB, SA, FP prepared, performed and analyzed radial velocity observations;

ABa, MA, JS, ALé, ALl, PB contributed fundamentally to the definition, design and operation of the CoRoT instrument;

AE, BT, SC, RD, MF, MG, MH, TL, HR, DR, RS, AS, HJD, RdH, RA, DC performed ground-based photometry;

SC, RA, MB, ABo worked on light curve modelling and parameter fitting;

MD, HB, DG, JCG, EG, BS, MF constitute the team that performed the stellar typing and related observations; and

TG, MH, JS, HL, GW, SFM performed the modelling of the planet and the interpretation of its characteristics. All authors discussed the results and commented on the manuscript.

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Figure captions

Figure 1 | **Light curve and model fit of the CoRoT-9b transit. a,** Phase-folded light curve from CoRoT around the first observed transit of Corot-9b, with the phase set to zero at mid-transit. The data from the three color-bands of CoRoT have been summed to a 'white' band and the points have been binned from an original cadence of 32 seconds to a duration of 96 seconds; the error bars indicate the dispersion of the points within the bins. The second transit observed by CoRoT is not shown, as it was only partially detected; its first 2 hours had been lost in an instrument interruption. The solid line represents the model fit from which the primary fit-parameters in Table 1 have been derived. They indicate a transit close to the equator, and a stellar limb darkening that is in good agreement with predictions for the CoRoT pass band[17]. This fit was based on the white-light data of the first transit event and included the removal of a 2.5% contaminating fraction of light not originating from CoRoT-9; the generation of a model for the planetary transit[18] assuming a linear relation for the stellar limb-darkening; and the fitting of the model using a heuristic optimization algorithm[19]. The contaminating fraction of 2.5% was determined from pre-launch imagery[20], taken with the INT/WFC on La Palma, after convolving these images with CoRoT's point-spread function, and measuring the contribution of nearby stars within CoRoT's aperture mask. **b**, residuals after subtraction of the model fit.

Figure 2 | **Corot-9 radial velocities**. Radial velocity data from HARPS after subtraction of the systemic velocity, versus the orbital phase, set to zero at periapsis. The solid line is the best-fit elliptical orbital solution, with an rms of its residuals is 6.3 m/s. This solution was also constrained by the known ephemeris of the planetary transits. An Ftest comparing a best-fit circular orbit against the adopted elliptic one gives a 95% confidence for the presence of an ellipticity that is significantly different from zero.

Figure 3 | **Evolutionary model for a CoRoT-9b like planet**. Shown are constraints on the transit radius of CoRoT-9b and for a given age, based on stellar[21] and planetary evolutionary tracks[22]. Note that its observed radius is 1.05±0.05 R_{jup} (Table 1). Red, blue and green dots correspond to models matching the ρ_s - T_{eff} uncertainty ellipse within 1, 2 and 3 sigma, respectively. Planetary evolution models for a planet with a solar-composition envelope and a central dense core of 0, 20, 40 and 60 Earth masses are shown as black, blue, green and light blue lines, respectively. They assume that the planet is made of a solar-composition envelope over a dense icy/rocky core of variable mass. Their results depend only weakly on the assumed opacities, and uncertainties on the atmospheric temperature, planetary mass, and any tidal dissipation rate are negligible.

Figure 4 | **The orbital parameters of CoRoT-9b among extrasolar planets**. Shown is the eccentricity and period of all 339 exoplanets for which both values are known as of Nov 1, 2009. Solid dots are the 58 transiting planets among them - most of them have short periods of <~5 days and zero or low eccentricities. Only two further transiting planets have orbital periods longer than 10 days; they are HD17156[23] with 21.2 and HD80806[24-26] with 111.4 days. However, both of them also have the highest eccentricity among planets of similar periods. Open dots are the remaining exoplanets, known only from radial velocity observations. Source: www.exoplanet.eu.

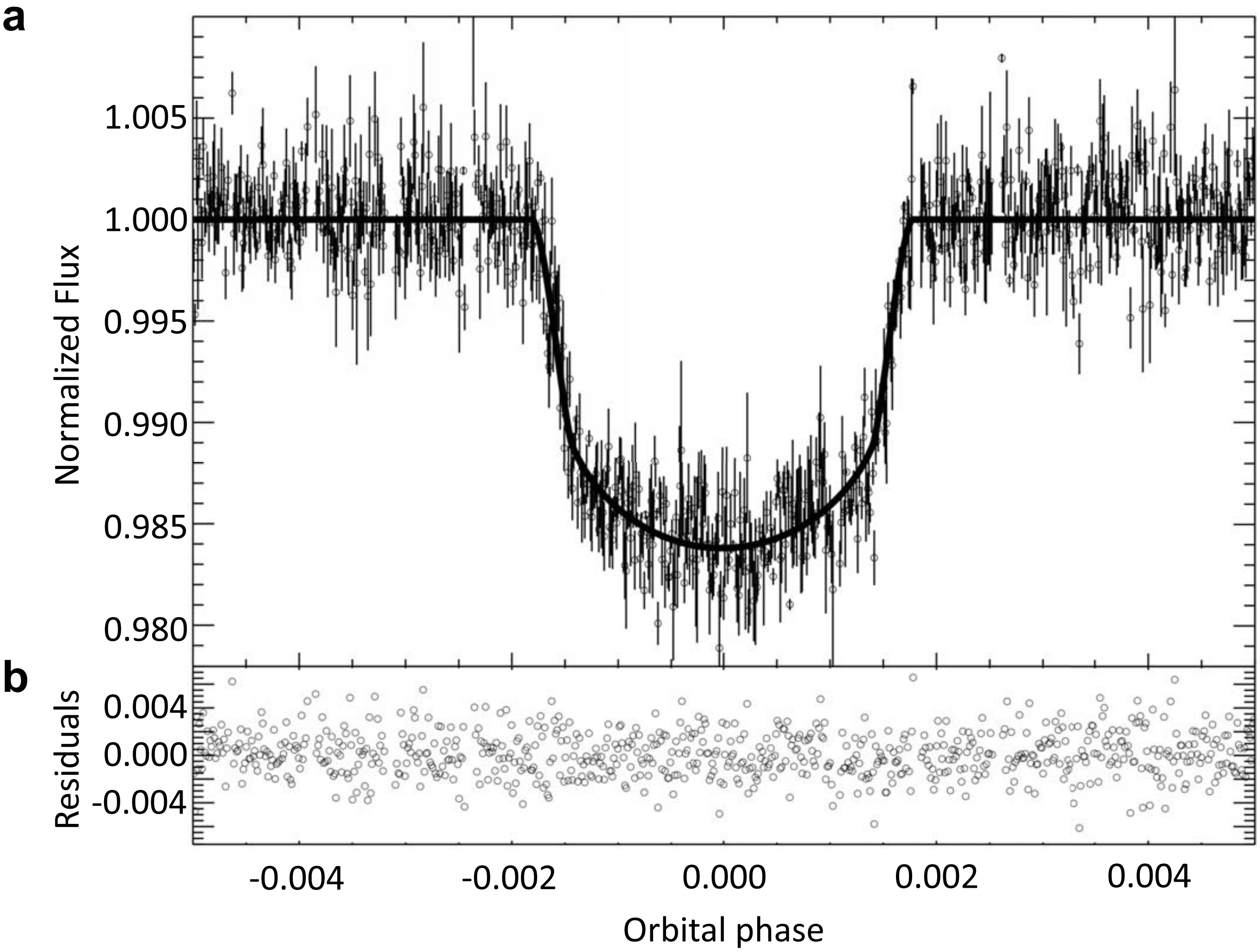
Table 1: Star and planet parameters of the Corot-9/9b system.

parameter	value
ID (CoRoT-Window-Id)	LRc02_E1_0651
ID (CoRoT/Exo-Dat)	0105891283
ID (GSC 2.3)	N1RO059308
position (J2000)	18:43:08.81 +06:12:15.19
magnitudes(a) U,B,V,r',i'	14.74, 14.55, 13.69, 13.33, 12.86
Results from light-curve analysis	
planet period P(b)	95.2738±0.0014 d
transit epoch T_0	HJD 24 54603.3447 +/- 0.0001
transit duration T_{14} (c)	8.08±0.10 h
relative transit depth $\Delta F/F_0$	0.0155±0.0005
radius ratio R_p/R_s	0.115±0.001
impact parameter b	$0.01^{+0.06}_{-0.01}$
limb-darkening coeff. u	0.57±0.06
ratio a/Rs (d)	93±3
inclination i (d)	> 89.95 deg
stellar density ρ_s (d)	1.68±0.20 g/cm^3
$M_s^{1/3} / R_s$ (d)	1.06±0.04 (solar units)
Results from radial velocity observations	
RV semi-amplitude K	38±3 m/s
orbital eccentricity e	0.11±0.04
argument of periastron ω	37^{+9}_{-37} deg

systemic radial velocity	19.791±0.002 km/s
mass function $f^{(e)}$	$(5.3\pm1.3)x10^{-10}$ M_{sun}
Results from spectral typing of Corot-9	
stellar spectral type(f)	G3V
stellar surface gravity $log\ g^{(g,h)}$	4.54±0.09
stellar effective temp. $T_{eff}^{(g)}$	5625±80K
metallicity [M/H] (g)	-0.01±0.06
stellar mass $M_s^{(i)}$	0.99±0.04 M_{sun}
stellar radius $R_s^{(j)}$	0.94±0.04 R_{sun}
stellar rotation. veloc. $v \sin i_{rot}$	≤ 3.5km/s
stellar rotational period P_{rot}	≥ 14 d
stellar distance	460 pc
Absolute physical parameters from combined analysis	
planet mass M_p	0.84±0.07 M_{jup}(k)
planet radius R_p	1.05±0.04 R_{jup}(l)
planet density ρ_p	0.90±0.13 g/cm^3
planet orbit semi-major axis a	0.407±0.005AU
planet-star distance at transit a_t	$0.377^{+0.025}_{-0.015}$AU

Notes: (a) Source: Exodat Information System, http://lamwws.oamp.fr/exodat/ (b) The period was determined from the first transit observed by CoRoT and from ground-based photometry of a transit on 5 Sep 2009, taken with the Euler 1.2m from La Silla, Chile, and the 2m Faulkes Telescope North at Haleakala Observatory. (c) The time from first to fourth contact is given. (d) These values consider also the eccentricity as found by the radial-velocity observations. (e) The mass function indicates the ratio $f = (M_p \sin i)^3 / (M_p+M_s)^2$ and is given by: $f = (1-e^2)^{3/2} K^3P/(2\pi\gamma,$ where γ is the gravitational constant.

(f) Based on data taken with the spectrograph (R ~ 2100) at the Thüringer Landessternwarte (Tautenburg, Germany) on 27 July 2008. (g) Based on high-resolution (R ~ 65000) spectra taken on 21 and 22 Sep 2008 with the ESO VLT/UVES in Dic1 mode (390+580) and a slit width of 0.7 arcsec and analysis with the VWA software[27,28]. (h) The value quoted is directly from spectroscopy. An alternative, *log g* = 4.49±0.04 can be derived from the stellar density given by the light-curve analysis and a weakly influencing a component of $M_*^{1/3}$. (i) Derived from StarEvol[29] evolutionary tracks. (j) Derived from the quoted stellar mass and the stellar density from the transit-fit. (k) R_{jup}= 71492 km. (l) $M_{jup} = 1.8986 \times 10^{30}$ g.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b
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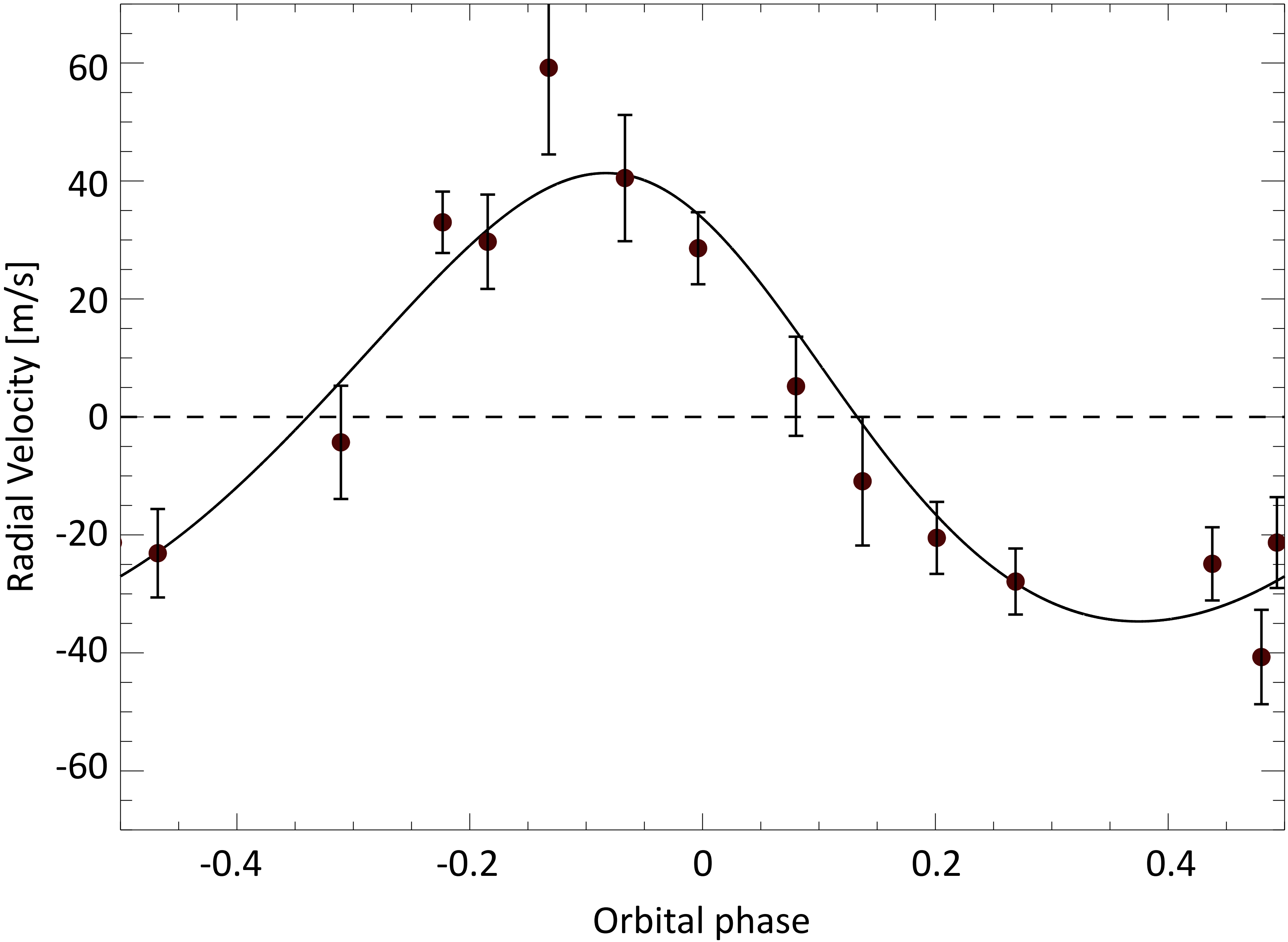
Orbital phase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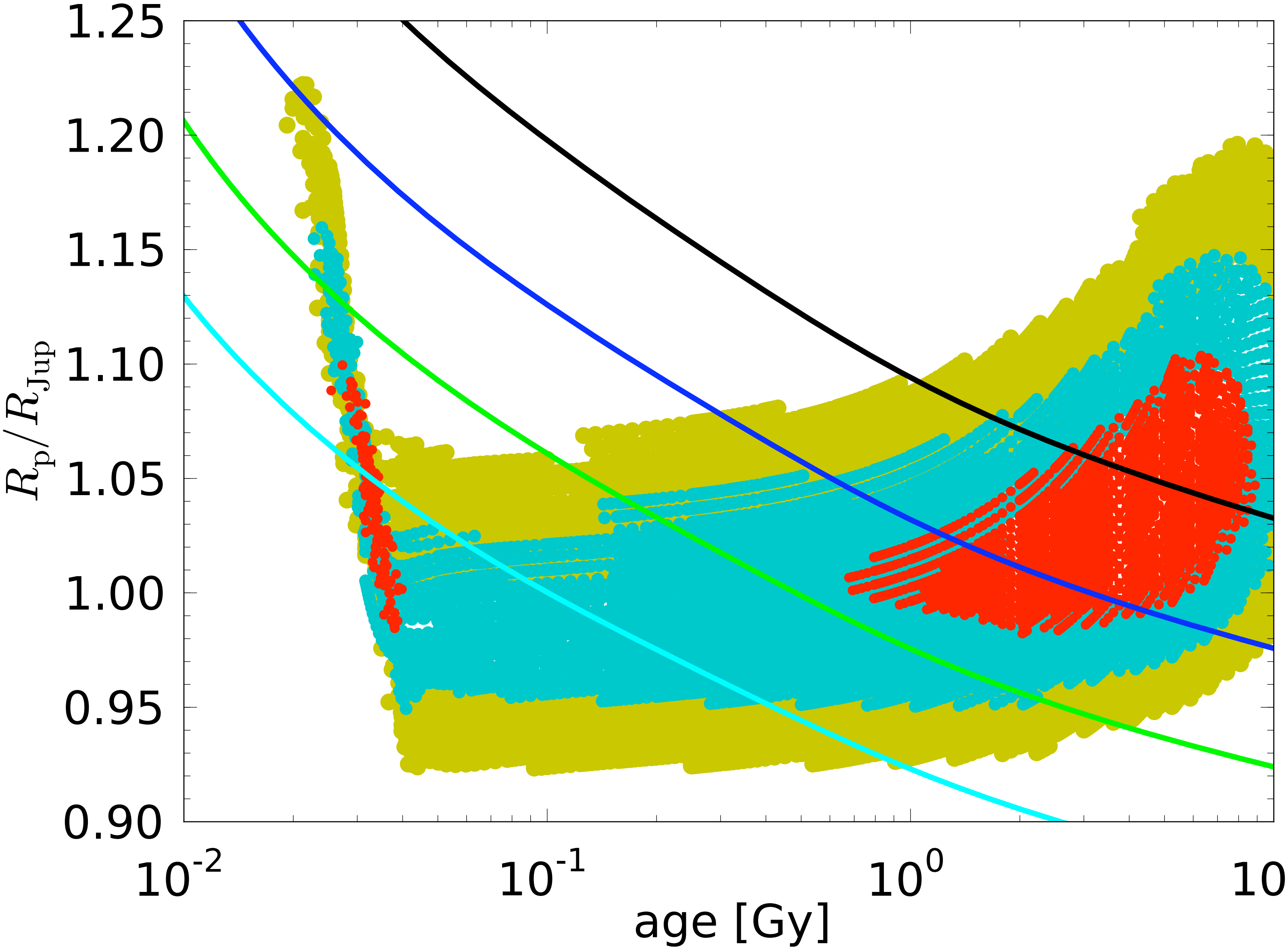
Orbital phase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1.20
1.15
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1.05
1.00
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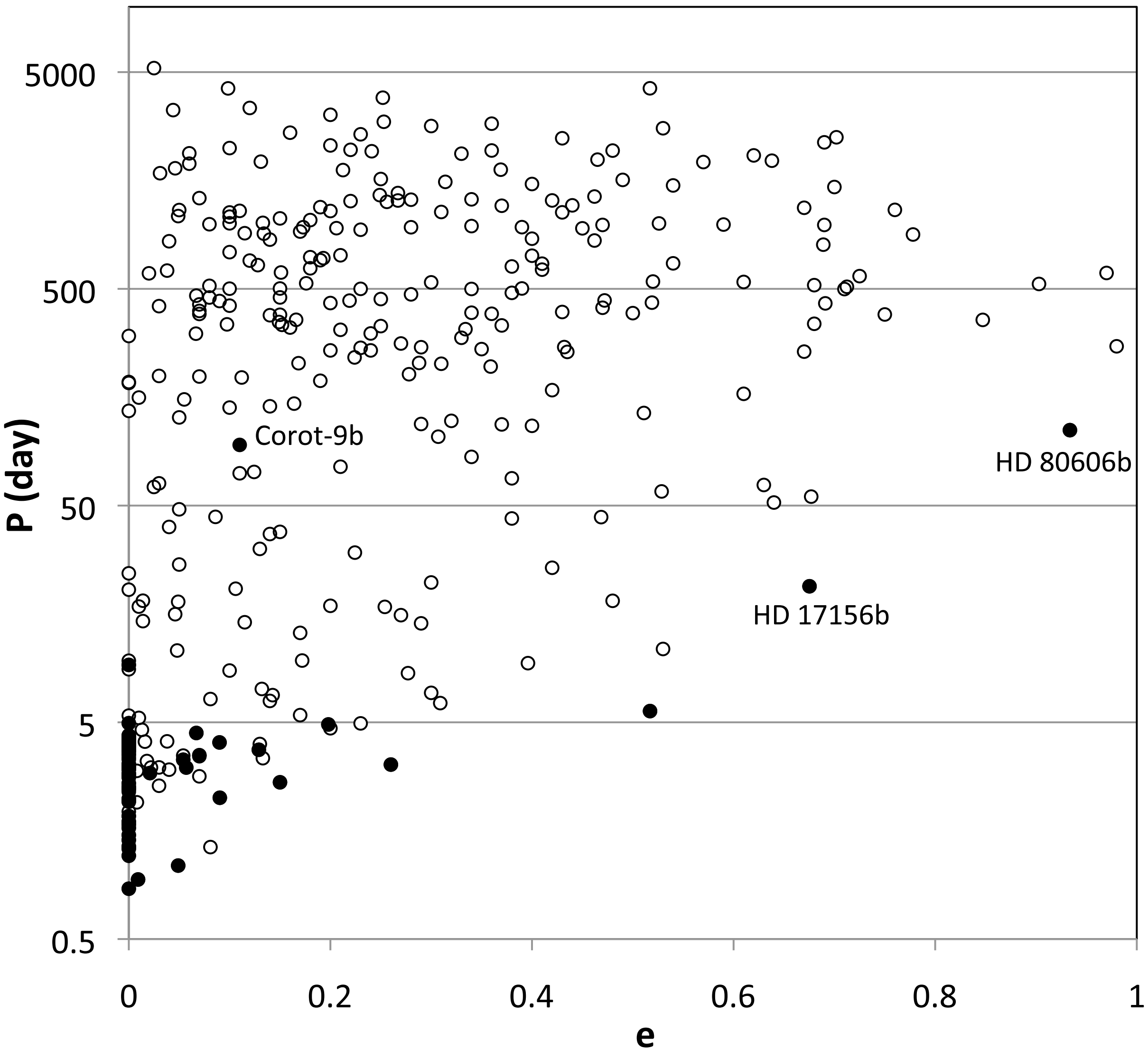
10^{-2}
10^{-1}
10^{0}
10^{1}
age [Gy]



P (day)
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5
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0.2
0.4
0.6
0.8
1
e
Corot-9b
HD 80606b
HD 17156b