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The CORALIE survey for southern extra-solar planets*

VI. New long period giant planets around HD 28185 and HD 213240

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Abstract. In this paper we present giant planetary companions to the stars HD 28185 and HD 213240. Both candidates were discovered in the context of the CORALIE extra-solar planet search programme. The planet around HD 28185, with a minimum mass of 5.7 $M_{\rm Jup}$ is one of the first long period planets (P = 383 days) discovered so far orbiting its host star in a nearly circular trajectory. On the other hand, the planet around HD 213240, with a 951-day period orbit, an eccentricity of 0.45, and a minimum mass of 4.5 $M_{\rm Jup}$, is more typical of the up to now discovered long period systems.

Key words. planetary systems – stars: individual: HD 28185 – stars: individual: HD 213240

1. Introduction

Following the discovery in 1995 of the planet orbiting 51 Peg (Mayor & Queloz 1995), we have witnessed a complete revolution in the field of extra-solar planets. More than 70 other exoplanets[1] were unveiled since then, all by means of high-precision radial-velocity techniques. These discoveries comprise 7 multi-planetary systems.

Two of the most prolific and precise planet search programmes are carried out by the Geneva group in both hemispheres, using the CORALIE spectrograph at the 1.2-m Euler Swiss telescope (e.g. Udry et al. 2000), at La Silla observatory (ESO, Chile) and, in collaboration with French colleagues, the ELODIE spectrograph (Baranne et al. 1996) at the 1.93-m telescope of the Haute-Provence observatory (France). In total, these two instruments have discovered (or in a few cases co-discovered) 32 planets, i.e. about half of the known systems[2].

Apart from a "few" exceptions, most of the extra-solar planets found to date have relatively short period orbits (shorter than 1 year). There are basically two reasons for this "bias". First, radial-velocity techniques are more sensitive to close companions; a long period companion must have, with respect to a shorter period one, a higher mass to produce a radial-velocity variation with the same amplitude. Second, to detect a long period planet one needs to follow a star during several seasons with the necessary long term precision. However, the ever increasing accuracy and continuity of some of the current radial-velocity surveys are now permitting to unveil more and more long period companions. In this paper we present two such candidates, recently discovered[3] in the context of the CORALIE programme, namely the companions around HD 28185 and HD 213240.

2. A long-period companion to HD 28185 in a circular orbit

2.1. Stellar characteristics

At a distance of ∼40 parsec (π = 25.28 ± 1.08 mas, from Hipparcos data – ESA 1997), HD 28185 (HIP 20723, BD −10 919) is a G5 dwarf shining with a visual magnitude $V = 7.8$ in the constellation Eridanus (the River). Its colour index is $(B-V) = 0.75$ as listed by the Hipparcos catalogue, and its absolute magnitude $M_v = 4.81$. The basic stellar parameters are summarized in Table 1.

Recently, we have derived atmospheric parameters for this star using a detailed spectroscopic analysis (Santos et al. 2001). The obtained $T_{\rm eff}$, $\log g$, microturbulence parameter ($\xi_{\rm t}$), and iron abundance ([Fe/H]) are 5705 K,

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* Based on observations collected at the La Silla Observatory, ESO (Chile), with the CORALIE spectrograph at the 1.2-m Euler Swiss telescope.

[1] By October 2001, 71 exoplanets were known having minimum masses below 10 $M_{\rm Jup}$.

[2] See table at http://obswww.unige.ch/∼naef/who_discovered_that_planet.html

[3] These two planets were announced with 9 other systems in an ESO Press-release (4th of April 2001), available at http://www.eso.org/outreach/press-rel/pr-2001/pr-07-01.html

Table 1. Observed and inferred stellar parameters for HD 28185 and HD 213240 with the corresponding references.

Parameter		HD 28185	HD 213240	References
Spectral Type		G5V	G4IV	HIPPARCOS (ESA 1997)
V		7.80	6.81	HIPPARCOS (ESA 1997)
$B-V$		0.750	0.603	HIPPARCOS (ESA 1997)
π	[mas]	25.28 ± 1.08	24.54 ± 0.81	HIPPARCOS (ESA 1997)
M_V		4.81	3.76	
$L/L_\odot$		1.02	2.59	Flower (1996)
[Fe/H]		+0.24	+0.16	Santos et al. (2001); Spectroscopy
$M/M_\odot$		0.99	1.22	Geneva models, Schaerer et al. (1993)
$T_{\rm eff}$	[K]	5705	5975	Santos et al. (2001); Spectroscopy
$\log g$	[g cm^{-2}]	4.59	4.32	Santos et al. (2001); Spectroscopy
$v \sin i$	[km s^{-1}]	2.54 ± 1.02	3.97 ± 0.61	CORAVEL (Benz & Mayor 1984)
$\log(R'_{\rm HK})$		-4.82	-4.80	Strassmeier et al. (2000); Santos et al. (2000a)
$P_{\rm rot}(R'_{\rm HK})$	[days]	30	15	Noyes et al. (1984)
age	[Gyr]	2.9/7.5	2.7/4.6	Donahue (1993)/Geneva models

4.59 dex, 1.09 km s^{-1}, and +0.24 dex, respectively, typical parameters for a metal-rich G dwarf. The high [Fe/H] value is compatible with the one listed by Laughlin et al. (2000) who used *ubvy*-photometry calibrations. A similar value of +0.15 is obtained from a calibration of the CORALIE cross-correlation dip[4]. The stellar mass and age, determined from the Geneva theoretical isochrones of Schaerer et al. (1993) using M_v and the obtained $T_{\rm eff}$, are $0.99 \pm 0.07\,M_\odot$ and ∼7.5 Gyr, respectively. This age is compatible with the fact that only an upper value for the Li abundance was found (Israelian et al., in preparation).

Strassmeier et al. (2000) have derived a value of −4.82 for the chromospheric activity index $\log R'_{\rm HK}$. This corresponds to a non active dwarf (see e.g. Henry et al. 1996), with an age of ∼3 Gyr, as derived from the calibration of Donahue (1993) – also presented in Henry et al. (1993).

2.2. Planetary signature of HD 28185

Between October 1999 and September 2001 we obtained 40 high-precision radial-velocity measurements[5] of HD 28185 – see Fig.1. An analysis of the data revealed a periodic variation; the best Keplerian solution gives a period of 383 days, an amplitude of 161 m s^{-1} and an eccentricity of 0.07. The obtained value for the eccentricity is compatible with a circular orbit according to the Lucy & Sweeney (1971) test. In Table 2 we present the derived orbital and planetary parameters.

Since the period is close to one year, some problems arise when trying to completely cover the orbital phase. Even if the orbital parameters are quite well constrained, some uncertainties are present; we hope to eliminate them when more data will be added during the next season.

Given the mass for the star, the observed radial-velocity variation is best interpreted as the signature of a planetary companion with a minimum mass of $5.7\,M_{\rm Jup}$. The combined CORALIE and old CORAVEL measurements show sign of a possible (but not clear) radial-velocity drift over 10 years. On the other hand, the residuals around the CORALIE orbital solution suggest the presence of a second longer period companion, but the detection is, up to now, only marginal. HD 28185 is noted as "single" in the Hipparcos catalogue (ESA 1997).

With a minimum mass of $5.7\,M_{\rm Jup}$, some questions might arise concerning the real nature of the discovered companion. We note, however, that the probability that its mass is in the Brown-Dwarf regime is of the order of 10%, and thus we think it is reasonable to refer to this companion as a planet.

In fact, further support to this comes from geometrical considerations. The $v \sin i = 2.54 \pm 1.02$ km s^{-1} derived for HD 213240 (from the CORAVEL cross-correlation function – Benz & Mayor 1984) together with the rotational period estimated from the activity level of the star (30 days from the calibration of Noyes et al. 1984), strongly suggest a value for $\sin i$ close to unity, i.e., the star seen "equator-on". Assuming that the orbital plane is perpendicular to the rotation axis (this is approximately true for the case of the Solar System, and verified for HD 209458 – Queloz et al. 2000), we conclude that the measured minimum mass is most probably a good estimate of the real mass of the planet.

Activity related phenomena may induce radial velocity "jitter" (Saar & Donahue 1997; Santos et al. 2000a). For HD 28185, the scatter around the Keplerian orbital solution is around 10 m s^{-1}, while the mean photon-noise error of the measurements is ∼6 m s^{-1}. Subtracting quadratically we obtain a "jitter" of 8 m s^{-1}, lower than (but compatible to) the ∼10 m s^{-1} expected (in average) for a G dwarf with $\log R'_{\rm HK} = -4.82$ (Santos et al. 2000a).

A look at the Hipparcos catalogue (ESA 1997) shows that the scatter in magnitude is about 0.012 (in 117 measurements). Although relatively high, this value is typical for an 8th magnitude star; HD 28185 is labeled constant in the catalogue.

[4] See Mayor et al. (1980), Pont (1997) or footnote in Santos et al. (2001) for the description of the technique.

[5] The CORALIE individual radial-velocity measurements presented in this paper for both HD 28185 and HD 213240 are available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/379/999`

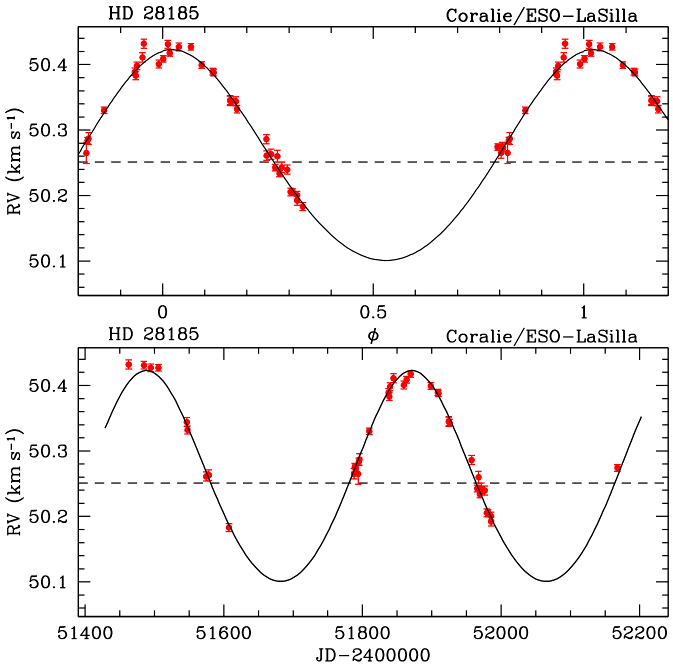

Fig. 1. *Top*: phase-folded radial-velocity measurements for HD 28185. *Bottom*: radial-velocity measurements as a function of time for the same star. The 40 measurements span about 2 years. Error-bars represent the photon noise error.

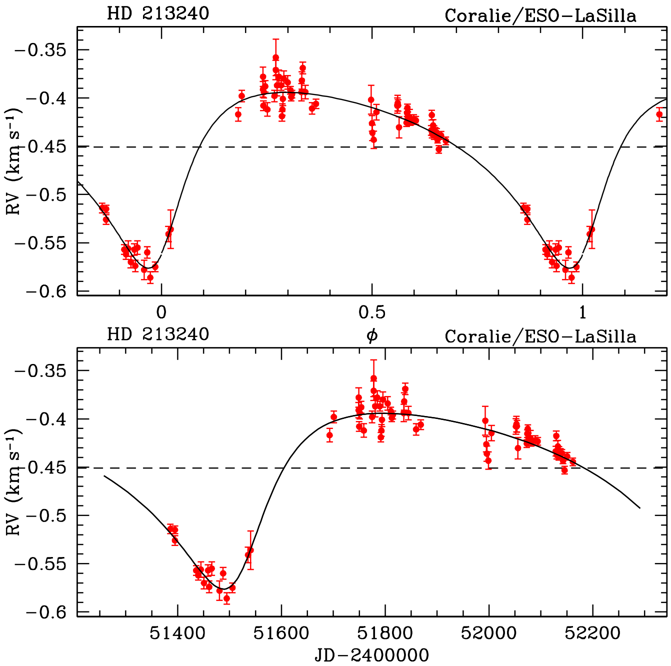

Fig. 2. Same as Fig. 1 for HD 213240. The 72 measurements span about 2 years.

Bisector changes can be used as a diagnostic of activity induced radial-velocity variations. Although we did not expect that activity related phenomena could be able to produce the observed radial-velocity signature[6], we have analyzed the inverse slope of the bisector of the CORALIE cross-correlation function (Queloz et al. 2001). The analysis revealed no significant bisector variations. Given the long orbital period, and the lack of any significant signature in the Hipparcos astrometry (F. Arenou, private communication)[7], it is quite difficult to imagine that another cause, besides the presence of a planet, could induce the observed radial-velocity variation.

3. A long period planet around HD 213240

3.1. Stellar characteristics

HD 213240 (HIP 111143, CD −50 13701 A) is a high proper-motion 6.8 magnitude G0 dwarf in the southern constellation Grus (the Crane). Its colour index $(B-V)$ is 0.60 – from the Hipparcos catalogue (ESA 1997) – and from the parallax measurements its distance is ∼40 parsec ($\pi = 24.54 \pm 0.81$ mas) implying an absolute visual magnitude $M_v = 3.76$. The basic stellar parameters for HD 213240 are summarized in Table 1.

From a high S/N CORALIE spectrum we have derived the stellar atmospheric parameters for HD 213240. The technique used is well described in Santos et al. (2000b, 2001). The obtained $T_{\rm eff}$, surface gravity, microturbulence parameter and iron abundance ([Fe/H]) are 5975 K, 4.32 dex, 1.29 and +0.16, respectively. The derived effective temperature is about 200 K higher than the value of 5770 K obtained from *ubvy*-photometry of Olsen (1994) and the calibrations in Schuster & Nissen (1989), and 100 K above the value of 5880 K derived from the calibration of $T_{\rm eff}$ vs. $B-V$ presented by Flower (1996). As for the [Fe/H], the result determined from the *ubvy*-photometry calibration (−0.16) is not compatible with the +0.16 obtained from our fully spectroscopic analysis[8]. Finally, using the Hipparcos parallax we derive a surface gravity $\log g = 4.10$ for HD 213240 (e.g. Allende-Prieto et al. 1999), quite lower than the 4.32 dex obtained from our analysis. We do not completely discard, however, that the star may be already a bit evolved, given that the surface gravities derived from our spectroscopic analysis have usually higher values that the ones computed using e.g. Hipparcos parallaxes.

Using $T_{\rm eff} = 5975$ K and [Fe/H] = +0.16 from the more precise spectroscopic analysis, and the luminosity derived from the calibration of Flower (1996), we obtain an age of 4.6 ± 0.2 Gyr and a stellar mass of $1.22 \pm 0.01\,M_{\odot}$ (from the Geneva evolutionary tracks – Schaerer et al. 1993).

[6] The rotational period of the star is much shorter than the observed period in the radial-velocity data. Furthermore, the activity cycle of a solar-type star is not expected to produce amplitudes higher than a few m s^{-1} (McMillan et al. 1993).

[7] Note, however, that these constraints are not very strong, since the expected perturbation of a minimum mass planet is around 10^{-4} arcsec, i.e., about 10 times lower than the precision of the Hipparcos astrometry (e.g. Halbwachs et al. 2000). The same is true for HD 213240 (see below).

[8] This value is very close to the +0.23 derived from a calibration of the CORALIE cross-correlation function surface, further attesting the precision of this calibration.

Table 2. CORALIE best Keplerian orbital solutions derived for HD 28185 and HD 213240 and inferred planetary parameters.

Parameter		HD 28185	HD 213240
P	[days]	383 ± 2	951 ± 42
T	[JD]	51863 ± 26	51520 ± 11
e		0.07 ± 0.04	0.45 ± 0.04
V	[km s^{-1}]	50.251 ± 0.007	-0.451 ± 0.002
ω	[deg]	351 ± 25	214 ± 7
K	[m s^{-1}]	161 ± 11	91 ± 3
$N_{\rm mes}$		40	72
σ(O–C)	[m s^{-1}]	10	11
$a_1 \sin i$	[Gm]	0.85 ± 0.06	1.06 ± 0.06
$f(m)$	[$10^{-7}\ M_\odot$]	1.64 ± 0.33	0.53 ± 0.06
m_1	[$M_\odot$]	0.99	1.22
$m_2 \sin i$	[$M_{\rm Jup}$]	5.7	4.5
a	[AU]	1.03	2.03
$T_{\rm eq}$ †	[K]	250	180–300††

† In this paper we have used the albedo of Jupiter (∼0.35) – Guillot et al. (1996) – since there are big uncertainties in the current models of exoplanet atmospheric structure, and that there are no direct measurements of the albedo for these objects (e.g. Burrows et al. 2001). The values for $T_{\rm eq}$ should consequently just be regarded as an approximation.
†† Range of $T_{\rm eq}$ corresponding to periastron and apoastron distances from the central star.

From CORALIE spectra we can compute a chromospheric activity index $S_{\rm cor}$ (Santos et al. 2000a), similar to the one derived at Mount-Wilson (Vaughan et al. 1978). We have obtained $S_{\rm cor} = 0.176 \pm 0.017$ (where the error indicates the rms around the mean of the 5 measurements, covering more than 1 year), corresponding to $S_{\rm MW} = 0.19$; this value is compatible with the one obtained by Henry et al. (1996) of $S_{\rm MW} = 0.16$ (in one measurement). Using $S_{\rm MW} = 0.19$, we obtain $\log R'_{\rm HK} = -4.80$, a value typical for a non-active dwarf, and an age of 2.7 Gyr (Henry et al. 1996; Donahue 1993).

3.2. Planetary signature of HD 213240

Using CORALIE measurements, a clear long period radial-velocity variation was found. The 72 high-precision radial-velocity measurements, spanning about two years, allow us to derive an orbital solution (see Table 2). In Fig. 2 we can see a phase-folded and a "temporal" radial-velocity diagram of the measurements. The best Keplerian fit holds a period of 951 days, an amplitude of 91 m s^{-1} and an eccentricity of 0.45. This corresponds to the expected radial-velocity signature of a planet with a minimum mass of $\sim 4.5\, M_{\rm Jup}$ orbiting at about 2.03 AU from the star. No long term significant drifts are evident in either the CORALIE and/or the CORAVEL data.

Non-identified long term drifts could in fact affect the estimation of the orbital eccentricity of the companion around HD 213240. This may be particularly true in this case, since the measurements still do not cover a complete orbital period. In order to test if the presence of a trend is responsible for the computed high-eccentricity, we have corrected the radial-velocities for the small drift present in the CORAVEL+CORALIE data (about 0.01 ± 0.01 m s^{-1} day^{-1}, and non-significant) and computed a new orbit. The result shows that the orbital parameters, and in particular the eccentricity and the residuals (O−C), remain unchanged. The same is true if we vary the slope of the linear correction within the uncertainties. We thus conclude that the "high"-eccentricity obtained for the planet orbiting HD 213240 does not seem to be explained by any unidentified short amplitude long term drift.

The projected rotational velocity of the star is $v \sin i = 3.97 \pm 0.61$ km s^{-1} (from CORAVEL measurements – Benz & Mayor 1984). From the chromospheric activity level, using the calibration of Noyes et al. (1984), we obtain a rotational period of 15 days. Given the temperature and luminosity of the star, we derive a stellar radius of ∼1.5 times the radius of the Sun. This radius and rotational period correspond to $V_{\rm rot} = 5.1$ km s^{-1}, and the derived $\sin i$ is thus ∼0.78, corresponding to an angle of about ∼50 degrees. This would mean that the mass of the planet is about 1.3 times higher than the measured minimum mass, if we assume that the orbital plane is perpendicular to the rotation axis of the star.

In any case, and as for HD 28185, we note that the probability that the companion has a minimum mass in the Brown-Dwarf regime is quite low (around 5% in this case), and thus the planetary explanation seems the most credible.

Hipparcos photometry (ESA 1997) show that the star is stable up to a precision of 8 mmag (158 measurements), a typical value for a dwarf of its magnitude. The rms around the radial-velocity orbital solution is 11 m s^{-1}, with an average photon-noise error of 6.5 m s^{-1} for the individual measurements. Subtracting quadratically, this gives a "jitter" of 9 m s^{-1}, as expected from Eq. (3) of Santos et al. (2000a). A Fourier-Transform of the residuals does not show any significant signature of a shorter period companion.

Pannunzio et al. (1992) have classified HD 213240 as the A component of a double system, where the B component (CD −50 13701 B) is a faint 12 magnitude star located about 20 arcsec away. At the distance of HD 213240, 20 arcsec correspond to a projected minimum distance of about 800 AU, and if the stars constitute a bound binary system, significant perturbations in the orbit of the planetary companion might be expected, at least if the orbit of the fainter (and less massive) stellar companion is eccentric (Rasio & Ford 1996). The presence of a longer period companion could indeed help to explain the eccentricity of the planetary orbit (see e.g. "similar" case of 16 Cyg A and 16 Cyg B – Cochran et al. 1997; Mazeh et al. 1997). There are, however, no indications from the available radial-velocity data that the objects are related, and the B component might just be a background star. In the Hipparcos catalogue HD 213240 is classified as a single star.

A search for an astrometric signature using Hipparcos data (F. Arenou, private communication) did not reveal any trace of a companion, confirming the low mass of the object orbiting HD 213240. Furthermore, no cross-correlation function bisector changes were found correlated with the radial-velocity. As for HD 28185, the presence of a planetary companion represents the only reasonable explanation to the observed radial-velocity variations.

4. Concluding remarks

We have presented giant-planet candidates around the stars HD 28185 and HD 213240. These two planets are both in long period orbits, and have minimum masses of 5.7 and 4.5 $M_{\rm Jup}$, respectively.

The main difference between these two systems is the eccentricity of the planetary orbits: while the planet around HD 213240 is quite typical of the now discovered long period planets (usually with high eccentricity), HD 28185 is one of the first long period but low eccentricity (lower than 0.1 and compatible with zero) planets found to date. The orbit of the planet orbiting HD 28185 is compatible with a circular trajectory with a period of 383 days (close to 1 Earth year). Its distance from the star, 155 million km, is almost equal to the distance between the Sun and the Earth. With the exception of the planet around HD 27442 ($P = 415$ days and $e = 0.06$ – Butler et al. 2001), circular or almost circular orbits amongst exoplanets had so far only been found for short-period systems, contrary to what is the case for the giant planets in our own Solar System.

The eccentricity distribution of planetary orbits is, today, one of the most interesting problems. As discussed in Udry et al. (2001) and Mayor & Santos (2001), with a few exceptions, there are no clear differences between the eccentricity distributions of planetary and stellar binary systems. This poses the problem of understanding how systems that were formed as the result of different physical processes (formation in a disk vs. instability collapse) may have similar eccentricity distributions.

For masses lower than $\sim$20 $M_{\rm Jup}$, it has been shown that the interaction with a gas disk has the effect of damping the orbital eccentricity (Papaloizou et al. 2001). This suggests that other processes, like the interaction between planets in a multiple system (e.g. Rasio & Ford 1996; Ford et al. 2001), or the influence of a distant stellar companion (e.g. Mazeh et al. 1997), may play an important role in defining the "final" orbital configuration.

Furthermore, another question is raised: what is the difference between these systems and our own Solar System? Although no real Solar System analogs were found to date, companions like the ones found orbiting HD 27442 and HD 28185, with relatively distant (more than $\sim$1 AU) giant planets in circular or almost circular orbits, may indeed help answer this question.

It has been shown that stars with giant planets are metal-rich when compared to "single" field dwarfs (Gonzalez et al. 1998; Santos et al. 2001). The Sun itself is in the "metal-poor tail" of the metallicity distribution of stars with planets (Santos et al. 2001). This fact make us wonder if the Solar System had or not a similar origin with the now found extra-solar planets, or at least a different evolution process. Although still too early to make any further statements, it is interesting to mention that both objects presented in this paper (HD 28185 with [Fe/H] = +0.24 and HD 213240 with [Fe/H] = +0.16) as well as HD 27442 ([Fe/H] = +0.22 from the spectroscopic study of Randich et al. 1999) seem to follow the general trend and are metal-rich with respect to the Sun.

The planet around HD 28185 is the first to be discovered around a middle age solar type dwarf, in a circular orbit, and located in the "habitable zone" where temperatures like those on the Earth are possible. Given the temperature of the star, at a distance of 1 AU the equilibrium temperature of the planet is 250 K. Still, it is most probably a giant, gaseous planet and thus an unlikely place for the development of life. Nevertheless, we can speculate that it may be orbited by one or more moons on which a more bio-friendly environment could have developed.

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