EPJ Web of Conferences **16**, 01001 (2011)
DOI: 10.1051/epjconf/20111601001

CoRoT's first seven planets: An overview*

R. Dvorak[1], J. Schneider[2], H. Lammer[3], P. Barge[4], G. Wuchterl[5]
and CoRoT team

[1] *Institute for Astronomy, Türkenschanzstrasse 17, 1180 Vienna, Austria*
[2] *LUTH, Observatoire de Paris-Meudon, 5 place J. Jansen, 92195 Meudon, Paris, France*
[3] *Space Research Institute, Austrian Academy of Sciences, Schmiedlstrasse 6, 8042 Graz, Austria*
[4] *Laboratoire d'Astrophysique de Marseille, Technopole de Marseille-Etoile, 13388 Marseille Cedex 13, France*
[5] *Thüringer Landessternwarte Tautenburg, Sternwarte 5, 07778 Tautenburg, Germany*

Abstract. The up to 150 day uninterrupted high-precision photometry of about 100000 stars – provided so far by the exoplanet channel of the CoRoT space telescope – gave a new perspective on the planet population of our galactic neighbourhood. The seven planets with very accurate parameters widen the range of known planet properties in almost any respect. Giant planets have been detected at low metallicity, rapidly rotating and active, spotted stars. CoRoT-3 populated the brown dwarf desert and closed the gap of measured physical properties between standard giant planets and very low mass stars. CoRoT extended the known range of planet masses down-to 5 Earth masses and up to 21 Jupiter masses, the radii to less than 2 Earth radii and up to the most inflated hot Jupiter found so far, and the periods of planets discovered by transits to 9 days. Two CoRoT planets have host stars with the lowest content of heavy elements known to show a transit hinting towards a different planet-host-star-metallicity relation then the one found by radial-velocity search programs. Finally the properties of the CoRoT-7b prove that terrestrial planets with a density close to Earth exist outside the Solar System. The detection of the secondary transit of CoRoT-1 at the 10^{-5}-level and the very clear detection of the 1.7 Earth radii of CoRoT-7b at 3.5 10^{-4} relative flux are promising evidence of CoRoT being able to detect even smaller, Earth sized planets.

1. INTRODUCTION

The space mission CoRoT is a joint adventure of different European countries, namely CNES, the French space agency as leading organisation and other ones in Austria, Brazil, Belgium, Germany and Spain and also the European Space Agency ESA. The original goal was to observe variable stars but – with the discovery of the first exoplanet in the early 90's – the search for exoplanets was included in the research program (see Schneider and Chevreton ([17]) and turned out to be also very important. Already in the name of the mission CoRoT both research tasks are mentioned **Co**nvection, **Ro**tation and planetary **T**ransits. The satellite was successfully launched on December, 27th 2006 from Baikonour, observations started in February 2007 and first results concerning extrasolar planet transits respectively an overview of the CoRoT mission were published by Barge et al. [4]. The life-time was scheduled for 3 years of observations and recently the extension for another three years was approved. Some of the results obtained with measurements of the CoRoT mission were published in a whole volume of the journal Astronomy and Astrophysics this year (Baglin et al. [6]).

*The CoRoT space mission has been developed and is operated by CNES with the contribution of Austria, Belgium, Brazil, ESA, Germany and Spain.

Because there exist already several introductionary papers describing the mission and the instrument in detail (like the one cited above by Barge et al.) we just mention the main characteristics of the satellite: The 4 m long and 630 kg massive satellite has a mean diameter of 2 m. The accuracy of the pointing is 0.5 arcsec with a capacity of the telemetry of 1.5 Gbit/day. Three systems are operating on the satellite:

1. **CoRoTel** is an afocal telescope with 2 parabolic mirrors and aperture of 27 cm a cylindric baffle 2 m long,
2. **CoRoTcam** is a wide field camera consisting of a dioptric objective of 6 lenses where the focal unit is equipped with 4 frame-transfer-CCD 2048x4096. Two of the four CCDs are for the exoplanet program and two are for the seismology program.
3. **CoRoTcase** is hosting the electronics and the software managing the aperture photometry processing.

For the exoplanet CCD the total number of stars is 12000 and the magnitudes are between 11 and 16; the flux is measured every 512 s consisting of 16 individual exposures of 32 s. A bi-prism in the focal block dedicated to exoplanets allows to get chromatic information (red, green and blue) for brighter stars, but for faint stars only the standard one band (white) photometry is performed. The polar orbit of the satellite allows to observe 150 days in the long run, and between 20 and 30 days in the short run, both in the direction of the center respectively anticenter of the milky way, which makes two reversal manoeuvres necessary per year.

Radial velocity measurements to confirm planet candidates were usually performed with the following instruments:

1. HARPS spectrograph in La Silla (3.6 m telescope)
2. SOPHIE spectrograph in the Observatoire de Haute Provence (1.93 m telescope)
3. CORALIE spectrograph on the 1.2 swiss telescope in La Silla
4. Coudé echelle spectrograph from the 2 m telescope Tautenburg (TLS)
5. UVES and FLAMES spectrographs in Chile
6. Spectrographs at McDonald observatory

2. COROT-1B: THE FIRST PLANET DISCOVERED BY COROT

Already the first exoplanet discovered by CoRoT measurements was a surprise concerning its nature (Barge et al. [5]): it turned out to have a very small density (0.38 g cm^{-3})[1] compared to all other planets found up to now. The short period of 1.5 days – the light curve is shown in Fig. 1 – gave a very well determined period because 34 successive transits could be used for its computation. Additional RV observation (Fig. 2) were undertaken from OHP with the SOPHIE spectrograph for 9 different positions of the exoplanet and confirmed the planetary nature of the transit of a planet with a radius of 1.49 R_{Jup} and a mass of 1.03 M_{Jup} in front of a G0V star. Later photometric observation revealed the secondary eclipse, when the planet disappears behind the disc of the star which was discovered despite a very shallow nature of the signal (Fig. 3).

3. COROT-2B: A TRANSITING PLANET AROUND AN ACTIVE G STAR

Out of 78 transits during the 150 days of observations of CoRoT-2b (Alonso et al. [2]) (Fig. 4) the composite light curve for the transit (Fig. 5) was derived after removing the signal of the star's rotation and activity, which is due to large spots on its surface. The respective periods were between 4.5 and 5 days and showed flux variations of a few percents. This second confirmed planet of CoRoT orbits a K0V

[1] In the text all the parameters are given without the error bars. The complete values with the estimated errors are given in the appendix.

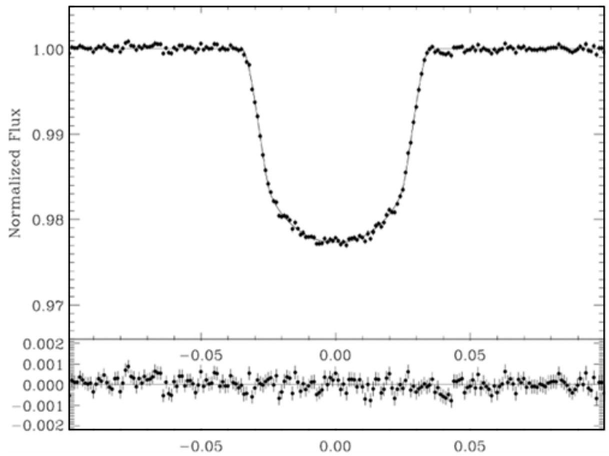

Figure 1. Normalised and phase-folded lightcurve of the best 34 transits of CoRoT-1b ([5] Fig. 1).

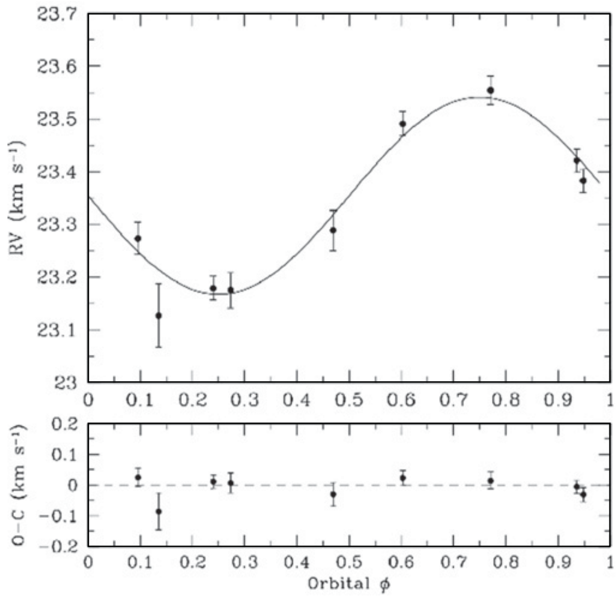

Figure 2. RV measurements of CoRoT-1b with SOPHIE ([5] Fig. 2).

star with a metallicity of [Fe/H] = 0 in 1.74 days and has a mass of 3.3 M_{Jup} and a radius of 1.465 R_{Jup}. With the use of very precise RV measurements with SOPHIE, HARPS and CORALIE it was possible to determine an inclination of $\lambda = 7.2^{\circ}$ between the planetary orbit and the equator of the central star ([7]). The radial velocity anomaly during the transit of the planet (Fig. 6) – the Rossiter-McLaughlin effect[2] was measured up to now only for 5 transiting exoplanets. This new measurements showed that

[2] The rotation of a star leads to a line broadening in the spectra because by the coming towards the observer and the moving away of different parts of the disc, consequently a blueshift respectively a redshift in the star's spectrum is observable. Now when the planet hosting star is in transit, it hides part of the disc which causes the observed mean redshift to vary and this redshift anomaly switches from negative to positive (or vice versa) and of the form of this anomaly the inclination of the planets' orbit with respect to the equator of the star can be determined.

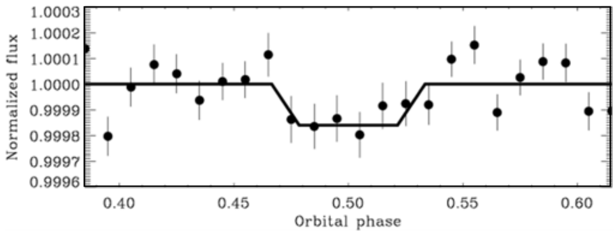

Figure 3. The secondary eclipse of CoRoT-1b ([3], Fig. 5).

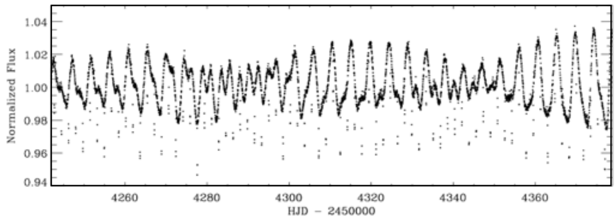

Figure 4. Normalized flux of CoRoT-2b using 78 transits ([2], Fig. 1).

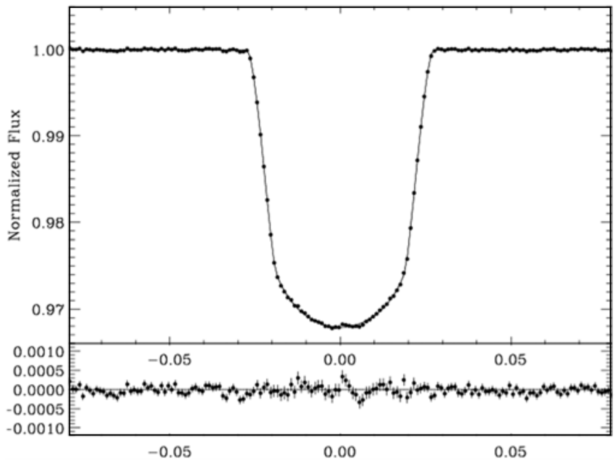

Figure 5. Normalized and phase folded light curve of 78 transits of CoRoT-2b ([2], Fig. 2).

even fainter stars ($m_v \leq 12$) transited by a planet can be used to determine this effect with telescopes of the 2 m class.

4. COROT-3B: THE FIRST SECURE INHABITANT OF THE BROWN DWARF DESERT

During the observations of 152 days from space a series of 34 transits (Fig. 8) could be measured for a young F3V star with a radius of $1.56 M_{Sun}$ with a period of 4.26 days (Fig. 7). The results were a big surprise because with a radius comparable to that of Jupiter the mass could be determined as $21.66 M_{Jup}$ which clearly distinguishes this planet from the normal close-in planets (Deleuil et al. [8]): either this is a brown dwarf or member of a new class of planets (Fig. 9). The determination of the mass was only possible with RV observations from the ground; in addition to the four mentioned instruments (HARPS, SOPHIE, CORALIE and TLS, Fig. 10) and measurements from McDonald observatory.

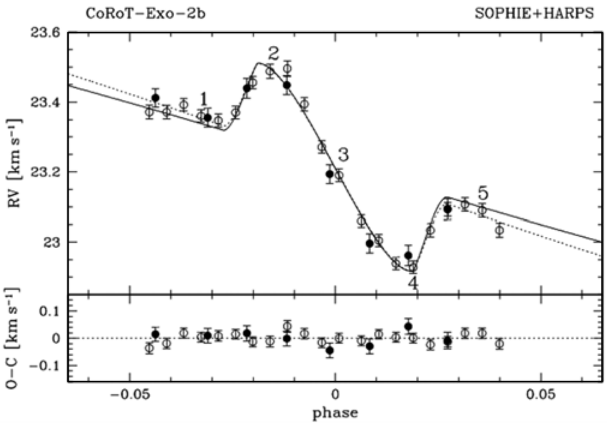

Figure 6. Phase-folded RV measurements of CoRoT-2b derived by SOPHIE and HARPS showing the Rossiter-McLaughlin effect during the transit ([7], Fig. 1).

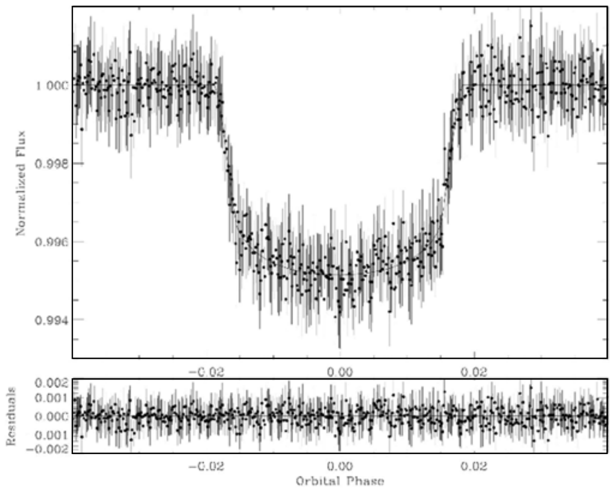

Figure 7. Light curve of CoRoT-3b ([8], Fig. 2).

5. COROT-4B: A TRANSITING PLANET IN A SYNCHRONOUS ORBIT

The planet itself with a radius of 1.2 R_{Jup} and a mass of 0.71 M_{Jup} is orbiting the host star with a period of 9.2 days on a circular orbit. The planet with its mean density of 0.525 g cm^{-3} is in the expected location of a Jupiter-like planet in the mass-radius diagram but because of its period of almost ten days lies outside of the other hot Jupiters with significantly smaller periods of $P \leq 5$ days (Aigrain et al. [1], Moutou et al. [13]). The reduction in luminosity caused by the planets' transit (Fig. 11) is in the order of 1.5 %. The subsequently undertaken RV measurements (Fig. 12) with HARPS and SOPHIE confirmed its planetary nature. From the lightcurve (not shown here) showing 6 clear transits during the continuous observation of almost 60 days one can see that the host star (a young F0V star of only about 1 Gyr of age) has an active surface with rapidly evolving starspots. It was possible to derive a rotation period of P = 8.87 days, which is within its error bars consistent with the period of the planet. In addition there could be an outer synchronized envelope of the star with differential surface rotation.

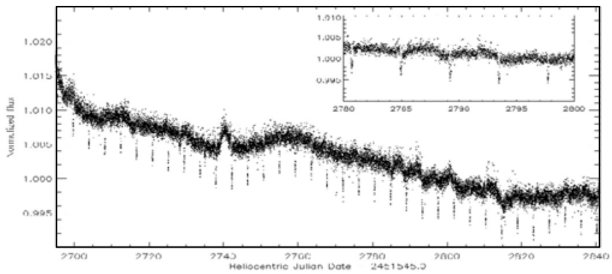

Figure 8. Light curve of CoRoT-3b for 152 days ([8], Fig. 1).

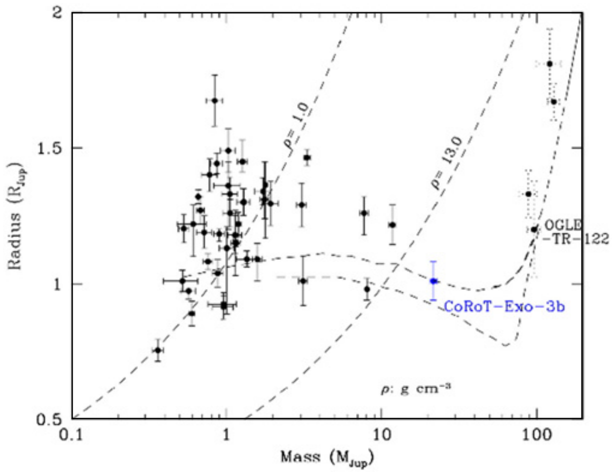

Figure 9. Mass radius diagram for transiting planets with CoRoT-3b in the brown dwarf desert ([8], Fig. 10).

6. COROT-5B: A HOT-JUPITER-TYPE PLANET

After an observation time of 112 days with 27 transits – Fig. 13 shows the light curve with a decrease in flux of 1.5% – the analysis led to an orbital period of 4 days, a radius of 1.4 R_{Jup} and a mass of 0.47 M_{Jup} (Rauer et al. [16]). The mean density of 0.217 g cm^{-3} is very low compared to other gas giants observed up to now[3]. This means that the planet shows the largest radius anomaly found so far. This relatively old star (5.5–8.3 Gyrs) is a F9V star with the mass of the sun and a slightly larger radius. Follow-up observations with SOPHIE and HARPS have been undertaken to derive the RV curve (Fig. 14) which clearly shows the Rossiter-McLaughlin effect. With additional HARPS observations it was possible to determine the very low metallicity (ratio [M/H] = −0.25).

7. COROT-6B: A TRANSITING HOT JUPITER PLANET IN A 8.9D ORBIT AROUND A LOW-METALLICITY STAR

This planet discovered by CoRoT turned out to be in a an orbit of P = 8.89 with approximately 3 Jupitermasses and a radius 15 percent larger than Jupiters' leading to a high density of 1.94 g cm^{-3} (Fridlund et al. [9]). It is hosted by a F9V star with approximately the mass of the Sun and a surprisingly

[3] Only the planets WASP-1b and WASP-15b (`http://exoplanet.eu`) have such low densities.

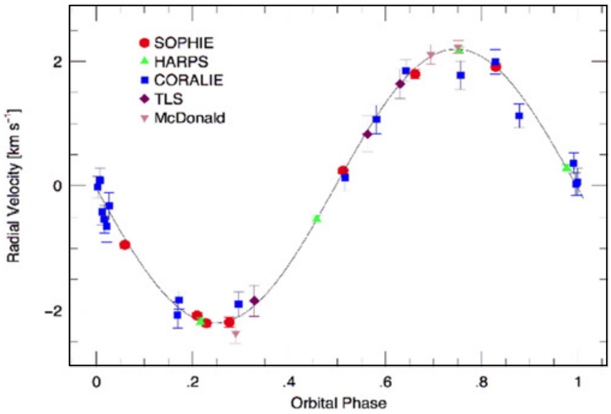

Figure 10. RV measurements of CoRoT-3b ([8], Fig. 4).

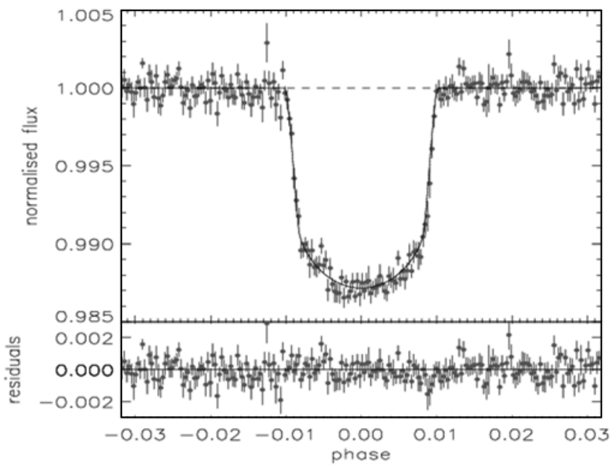

Figure 11. Folded light curve for CoRoT-4b ([1], Fig. 3).

low metallicity of $[Fe/H = -0.2]$. The combination of the RV measurements with the photometric ones from space – respectively ground-based photometric and spectroscopic observations – led to the full characterisation of the planet and the star. The respective results for the light curve (Fig. 15) and the RV measurements (Fig. 16) are taken from of [9].

8. COROT-7B: THE FIRST SUPER-EARTH WITH MEASURED RADIUS

The most exciting result of CoRoT up to now is the discovery of a Super-Earth planet with a terrestrial density orbiting extremely close to its host star. The G9V star is not older than 2 Gyrs and has a metallicity of 0.03 (Léger et al. [11]). CoRoT-7b turned out to be in a circular orbit in a distance of only approximately 4 times the radius of its host star which could be determined by the analysis of its 153 transits. The planets' radius is determined via photometric and spectroscopic measurements and turned out to be slightly smaller than 2 times the Earth's radius ($r = 1.78\ R_{Earth}$ and a mass of

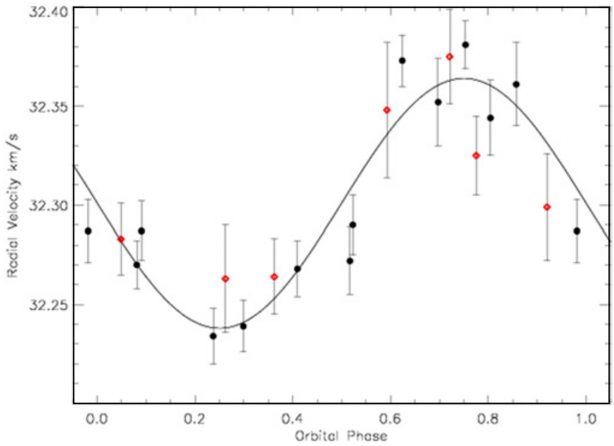

Figure 12. RV measurements of CoRoT-4b with HARPS and SOPHIE ([13], Fig. 2).

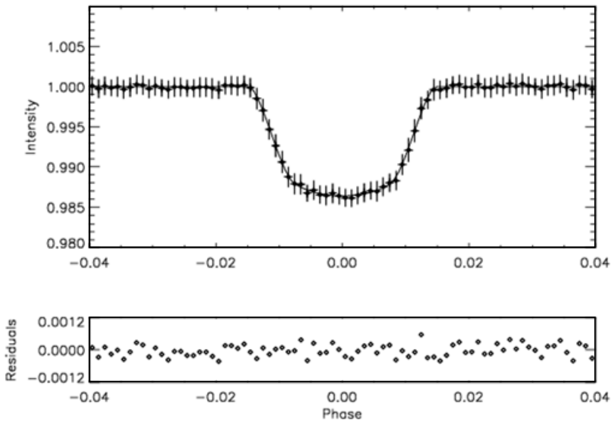

Figure 13. Phase-folded light curve of CoRoT-5b ([16], Fig. 6).

$M = 4.8\ M_{Earth}$) [4]. The mean density of 5.6 g cm^{-3} is comparable to the one of the Earth, consequently we can speak of an Earth-like planet which moves in only 0.854 days around the relatively young main sequence star which has a rotation period of 23 days. A second planet (Queloz et al. [15]) turned out to be on a 3.89 days orbit and is probably also a Super-Earth ($m = 8.4\ M_{Earth}$). It seems that both planets are made of of rocks or water and rocks similar to our Earth which can be understood from Fig. 18.

Because of the smallest period of CoRoT-7b found for a planet around another star the temperatures will be extremely high on its surface. Estimations for the temperatures on the day side (Schneider [18]) lead to a temperature of about 2000 K depending on the rotation of the planet; due to the vicinity to the star a bounded rotation is very probable. This would mean that the silicate surface consists of lava and the planets' atmosphere of evaporated silicates. On the contrary the far side could be in the temperature range such that water could be liquid or even be present on its surface in form of ice. In Fig. 19 there is a sketch of this planet where bounded rotation because of the acting tides of the star is assumed. This –

[4] These values are taken from the second paper on this planet ([15]); RV measurements in the first paper ([11]) were used to exclude non planetary companions.

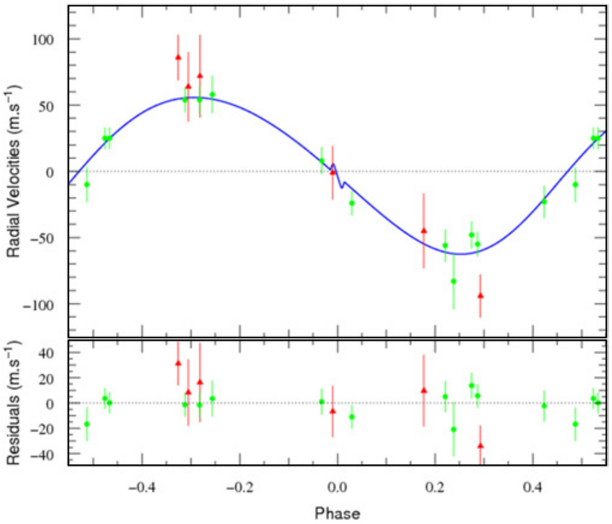

Figure 14. RV measurements of HARPS and SOPHIE showing the Rossiter-Laughlin effect of CoRoT-5b during the transit ([16], Fig. 2).

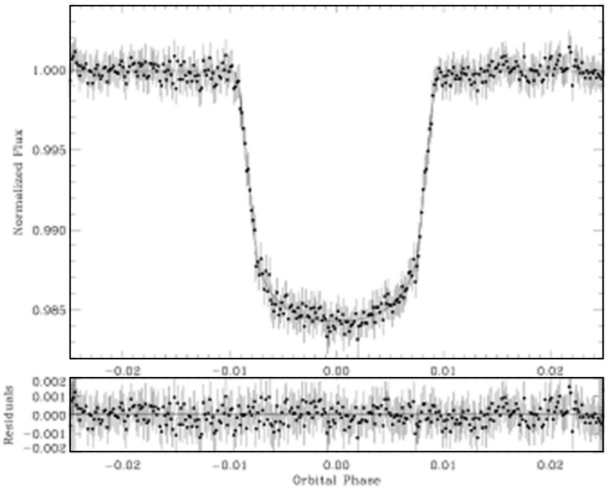

Figure 15. Phase-folded light curve of CoRoT-6b ([9], Fig. 4).

at least somewhat speculative – physical model has been drawn by J. Schneider [18] but it characterizes what kind of completely different appearance we may expect from the 'hells' planet.

With these measurements for CoRoT-7b it has been proven that the satellite is able to discover such planets as Super-Earth and even smaller ones. From Fig. 17 one can see that the very small amplitude transits of $\delta F/F \sim 3.5 \cdot 10^{-4}$ is clearly not the limit of detection.

9. THE MASS LOSS OF THE COROT PLANETS DUE TO PROXIMITY TO THE HOST STARS

In a recent study (Lammer et al. [10]) the thermal escape of hydrogen atoms from 57 transiting exoplanets was determined and a modified energy-limited mass loss equation applied, which reproduces

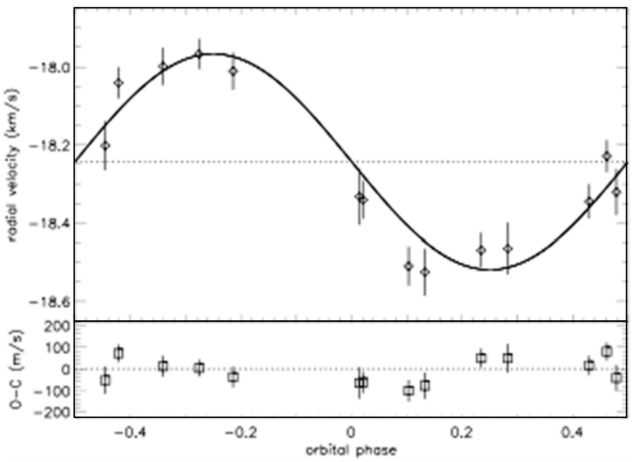

Figure 16. RV measurements of CoRoT-6b with SOPHIE ([9], Fig. 8).

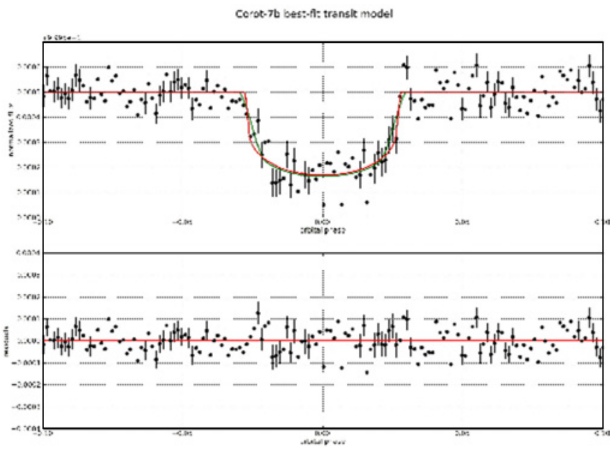

Figure 17. Superposition of 153 transits of CoRoT-7b ([11], Fig. 17).

the full hydrodynamic approach of studies (e.g. [14]). By applying the same method to the exoplanets discovered by CoRoT integrated over the life time of the planetary system we obtain for the given planetary and stellar parameters the thermal mass loss rates shown in Table 3.

Depending on the chosen stellar EUV-related heating efficiency η of 10 % or 25 % which corresponds to the ratio of the net local gas heating rate to the rate of stellar radiative energy absorption, one can see that CoRoT-1b and CoRoT-5b lost during their life-time about 1.3 % and 1.56 % ($\eta = 10$ %) or 3.07 % and 3.75 % ($\eta = 25$ %) of their initial masses. The thermal mass loss of CoRoT-2b, CoRoT-3b, CoRoT-4b and CoRoT-6b are lower and therefore negligible. The stronger mass loss effect for CoRoT-1b and CoRoT-5b are related to the lower planetary density, orbital distance and stellar parameters so that the Roche lobe becomes a relevant factor in the mass loss evolution of these planets.

Recently Leitzinger et al. ([12]) presented thermal mass loss calculations over evolutionary time scales to investigate whether CoRoT-7b could be a remnant of an initially more massive hydrogen-rich gas giant. The thermal mass loss results of these authors indicate that CoRoT-7b cannot be a remnant of a thermally evaporated Jupiter like gas giant. A scenario that CoRoT-7b is a remnant of an evaporated low density 'hot sub-Uranus' or 'hot sub-Neptune' is also very unlikely but can not be completely

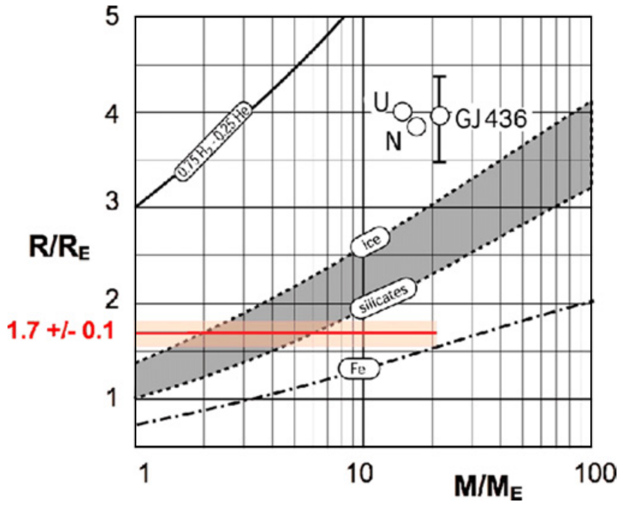

Figure 18. Location of CoRoT7-b in the mass-radius diagram ([11], Fig. 20).

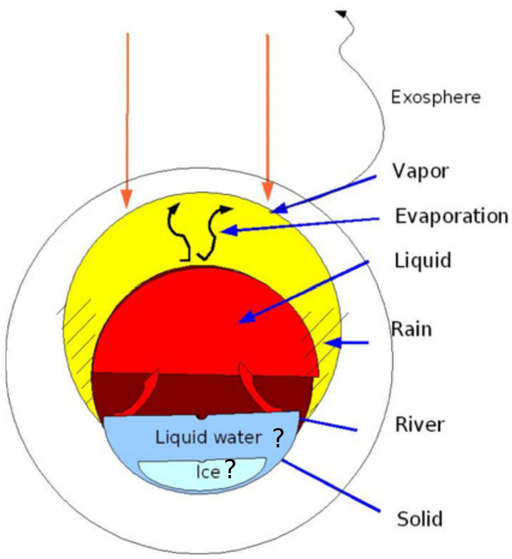

Figure 19. A physical model of CoRoT-7b ([18]).

excluded. Such an evaporation scenario would need, besides low initial density of the planet, also a heating efficiency of about 25% instead of more realistic 10% and an unlikely short exosphere formation time of less than 50 Myr. From these simulations one can conclude that CoRoT-7b was most likely never a gas or ice giant which has lost its entire hydrogen envelope, but started its evolution as a 'super-Earth' which could have lost a thin hydrogen envelope.

The efficiency of the CoRoT exoplanet mass loss is connected to the Roche lobe effect together with low planetary densities. Depending on the stellar luminosity spectral type, initial planetary density, stellar EUV-related heating efficiency, orbital distance, and the connected Roche lobe effect, one can expect that at orbital distances ≤ 0.015 AU, low density hot gas giants in orbits around solar type stars

Table 1. The astrophysical parameters of the host stars.

star	type	M/M_{sun}	age [Gyrs]	[Fe/H]
CoRoT-1	G0V	0.95	?	-0.3
		± 0.15		± 0.25
CoRoT-2	K0V	0.97	?	0.0
		± 0.06		± 0.1
CoRoT-3	F3V	1.37	$2.0^{+0.8}_{-0.4}$	-0.02
		± 0.09		± 0.06
CoRoT-4	F0V	$1.1^{+0.03}_{-0.02}$	$1.0^{+1.0}_{-0.3}$	0.0
				± 0.15
CoRoT-5	F9V	1.0	6.9	-0.25
		± 0.02	± 1.4	± 0.06
CoRoT-6	F5V	1.055	?	-0.2
		± 0.055		± 0.1
CoRoT-7	G9V	0.93	$1.5^{+0.8}_{-0.3}$	0.03
		± 0.03		± 0.06

may even evaporate down to their core size. Therefore, various size and mass type objects should be discovered in the near future.

10. CONCLUSIONS AND SYNOPSIS OF THE RESULTS

The observations from space with the satellite CoRoT turned out to have very interesting results for the knowledge of the diversity of planets and planetary systems. The continuous surveillance of 100000 stars for a period of 150 days is very efficient to detect close by planets (with periods between Venus and Mercury and smaller) and even allows to 'see' small planets transiting in front of the star's disk with a very small decrease in the flux like for CoRoT-7b. But to get absolute planetary parameters for the mass and the radius it is necessary to make extensive spectroscopic measurements and also to have a good knowledge of the astrophysical parameters of the host star. Only after careful analysis of the light curves (contamination may cause a 'false' alarm) in combination with thorough ground observation a confirmation of a planet found around another star can be attested.

The planets found by CoRoT are of extraordinary value for the extrasolar planetary research in astronomy because of the complete characterisation of the planets. One can see that most of the CoRoT planets are giant gas planets (radii between $0.97 \leq R_{Jup} \leq 1.49$. The largest ones (CoRoT-1b and 4b) are also very close to the host star having the shortest periods (1.51 and 1.74 days respectively) which is a clear sign of the important role of the star radiation on the radius evolution. CoRoT-4 and CoRoT-6 host planets which have a synchronized period with respect to the host stars' rotation. Concerning the metallicity it is interesting to note that three of the five hot Jupiters detected are orbiting metal poor stars, which is in contradiction to the normal metallicity relations found by RV searches. As last point it should be emphasized that the domain of planet masses covered by the CoRoT planets is within a wide range, namely from the very massive CoRoT-3b planet (with 21.6 M_{Jup}) to the telluric planet CoRoT-7b (0.015 M_{Jup}). Another new aspect is the discovery of close-in planets (CoRoT-7b and 7c). This can be regarded as hint that –like in our Solar System – planetary systems are 'full'. This means that in between two planets no other bigger objects (exceptions are asteroids) may exist on stable orbits.

The presentation of the major results in this overview is by far not complete – e.g. we did not speak about time transit variations (TTV) – which have also been detected in some of the data and may be caused by additional planets in the system. Only the results of the confirmed planets have been

Table 2. The orbital elements of the planets.

planet	Period [d]	a [AU]	inc [deg]	ecc
CoRoT-1b	1.508956 $\pm 6e-6$	0.0254 ± 0.0004	85.1 ± 0.5	0
CoRoT-2b	1.742996 $\pm 2e-6$	0.0281 ± 0.0009	87.84 ± 0.1	0
CoRoT-3b	4.2568 $\pm 5e-6$	0.057 ± 0.003	85.9 ± 0.8	0
CoRoT-4b	9.20205 $\pm 37e-5$	0.090 ± 0.001	90.0 $^{+0}_{-0.085}$	$0^{+0.1}_{-0}$
CoRoT-5b	4.037896 $\pm 2e-6$	0.04947 $^{+0.00026}_{-0.00029}$	85.83 $^{+0.99}_{-1.38}$	0.09 $^{+0.09}_{-0.04}$
CoRoT-6b	8.886593 $\pm 4e-6$	0.0855 ± 0.0015	89.07 ± 0.3	< 0.1
CoRoT-7b	0.85358 $\pm 2e-5$	0.0172 ± 0.0003	80.1 ± 0.3	0
CoRoT-7c	3.698 ± 0.003	0.046	?	0

Table 3. The physical properties of the planets.

planet	M/M_{jup}	R/R_{jup}	$\varrho[g\,cm^{-3}]$	Massloss [%]
CoRoT-1b	1.03 ± 0.12	1.49 ± 0.08	0.38	1.3–10.81
CoRoT-2b	3.31 ± 0.16	1.465 ± 0.029	1.31	0.06–0.59
CoRoT-3b	21.66 ± 1.00	1.01 ± 0.07	26.4	0.0002–0.0017
CoRoT-4b	0.72 ± 0.08	1.19 $^{+0.06}_{-0.05}$	0.525	0.12–1.212
CoRoT-5b	0.467 $^{+0.067}_{-0.024}$	1.388 $^{+0.046}_{-0.047}$	0.217	1.56– 12.78
CoRoT-6b	2.96 ± 0.34	1.166 ± 0.035	1.94	$\leq 1\%$
CoRoT-7b	0.015 ± 0.003	0.172 $^{+0.022}_{-0}$	4.23	?
CoRoT-7c	0.026 ± 0.003	?	?	?

presented[5], but the signals of many more planets seem to be still in our data like the ones of planets around double stars. But they can be confirmed only after difficult and long analysis combined with observations from the ground.

[5] In the appendix we show the star parameters and the derived parameters for the planets as published in the original papers.

11. APPENDIX

In table 10 the astrophysical parameters of the host stars are listed, in table 2 we listed the orbital parameters of the detected planets and in table 3 the physical parameters are given together with an estimation of the massloss due to the proximity to the star. All data are taken from the respective publications given in the text.

The LAM team and the Austrian team thanks CNES respectively ASA for funding the CoRoT project. The IAC team acknowledges the support of grants of the Education and Science Ministry. The German team (TLS and Univ. Cologne) acknowledges the support of DLR grants. For reading the manuscript and preparing an appropriate outlay of the pictures R. D. needs to thank A. Bazsó and V. Eybl.

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