Search for an exosphere around 51 Pegasi B with ISO[⋆]

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Abstract. The detection of absorption features in spectra of 51 Peg obtained during transit of its planet would provide a first clue on the physical nature of the planet. We have searched for signatures of an exosphere of the planet orbiting 51 Peg in the wavelength range from 2.39 μm to 3.5 μm and from 4.55 μm to 4.74 μm using SWS on ISO. Careful comparison of spectra taken during the transit of the planet with spectra obtained when the planet was not in the line-of-sight did not reveal any significant differences. We provide the S/N ratio and upper limits on the equivalent width of potential absorption lines in all wavelength bands. The upper limits on the equivalent width can be used for comparisons with predictions of the density of a potential exosphere of 51 Peg in future models.

Key words: techniques: spectroscopic – stars: atmospheres – stars: individual: 51 Peg B

1. Introduction

The discovery of planets in solar systems other than our own (inferred from periodic radial velocity variations (Mayor & Queloz 1995; Marcy & Butler 1995, 1998)) is certainly one of the major astronomical results of the decade. However, the faint planets have eluded direct detection searches so far, and apart from masses (which can only be estimated due to the uncertainties in sin i) and orbital parameters, their characteristics are unknown. This work is an attempt to obtain information on the planet 51 Peg B (Mayor & Queloz 1995) from spectroscopic observations of the star 51 Peg when the planet crossed the line-of-sight towards the Earth.

Six 51 Peg B-like planets with orbital distances smaller than 0.06 AU have been detected so far, orbiting stars 51 Peg (G2IV), HD 75289 (G0V), HD 187123 (G5), υ And (F8V), HD 217107 (G8IV) and τ Boo (F7V). These systems have a rather high probability of being eclipsing, which is of the order of 10%. Seven other planets orbit closer than 0.25 AU to their star, with eclipsing probabilities of 4% or more: 55 Cnc (G8V), ρ Cnc B (G1.5V), Gl 876 (M4V), HD 195019 (G3IV-V), Gl 86 (K1V), HD 168443 (G5) and HD 114762 (F9V). None of the stars have been observed to have photometric variations compatible with planetary eclipses. Only recently a transit event has been observed in HD209458 (G0V) (Henry et al. 1999). Evolution models predict that the planetary companions are able to survive the huge stellar insolation, and that they should have radii slightly above the radius of Jupiter ($R_J \approx 70000$km) if consisting of hydrogen and helium, or of the order of $1/3R_J$ in the unlikely case they mainly consist of silicates (Guillot et al. 1996, 1997). The photometric variation associated with a planetary transit would then be $\sim 10^{-2}$ and 10^{-3}, respectively.

Even in the absence of planetary transits, spectroscopic variations may arise due to the existence of an extended exosphere around the planet (Coustenis et al. 1997a,b). Giant planets at small orbital distances receive a tremendous amount of thermal energy by their parent stars, and have to fight a powerful stellar wind. As a result, significant mass losses are predicted (Guillot et al. 1996; Lin et al. 1996) which could amount to $10^{-16}M_\odot$/yr. Interactions with the stellar wind may further enhance these losses (Schneider et al. 1997; Chassefière 1997). The resulting exosphere, formed from dissociated and ionized escaping molecules and atoms, may pass in front of the star even if the planet itself does not.

We have chosen the 51 Peg system to search for a spectroscopic detection of a possible planetary exosphere using the Infrared Space Observatory (ISO). The orbital period of 51 Peg is 4.2293 ± 0.0011 days and corresponds to 0.05AU orbital distance (Mayor & Queloz 1995; Marcy et al. 1997). The small $m \sin i$ of the planetary companion, $0.47 M_J$ (M_J: Jupiter mass) and its high effective temperature, lead to a relatively large radius of $1.2 - 1.4 R_J$ in the case of a hydrogen-helium planet (Guillot et al. 1997). The rotation axis of 51 Peg is almost perpendicular to the line of sight (François et al. 1996). With the assumption that the planet rotates close to the stellar equatorial plane it is likely that a transit of the planet's exosphere can occur, although the upper limit for photometric variations in 51 Peg has led to the constraint i $< 85°$ (Henry et al. 1997) which suggests that it is not a fully eclipsing system.

Table 1. Log of the observations performed with SWS. Date and UT time of the predicted transits and the corresponding dates/times of the observations are given.

target	predicted transit time*	start date/UT time	end date/UT time	wavelength range μm
51 Peg A & B	07.07.97 00:08	06.07.97 23:57:58	07.07.97 00:51:09	2.38-2.60
51 Peg A & B	07.07.97 00:08	07.07.97 00:51:53	07.07.97 02:03:35	2.60-3.02
51 Peg A & B	02.12.97 02:23	02.12.97 01:43:42	02.12.97 03:11:53	3.02-3.52
51 Peg A & B	14.12.97 19:01	14.12.97 19:04:57	14.12.97 19:18:57	4.55-4.75
51 Peg A & B	14.12.97 19:01	14.12.97 19:19:41	14.12.97 19:33:41	4.55-4.75
51 Peg A & B	19.12.97 00:33	19.12.97 00:33:04	19.12.97 00:47:04	4.55-4.75
51 Peg A & B	19.12.97 00:33	19.12.97 00:47:46	19.12.97 01:01:46	4.55-4.75
51 Peg A & B	19.12.97 00:33	19.12.97 01:02:30	19.12.97 01:16:30	4.55-4.75
51 Peg A & B	19.12.97 00:33	19.12.97 01:17:12	19.12.97 01:31:12	4.55-4.75
51 Peg A	-	04.07.97 13:46:26	04.07.97 14:39:38	2.38-2.60
51 Peg A	-	04.07.97 14:40:22	04.07.97 15:51:54	2.60-3.02
51 Peg A	-	12.12.97 22:44:13	13.12.97 00:12:25	3.02-3.52
51 Peg A	-	13.12.97 00:13:09	13.12.97 00:27:09	4.55-4.75
51 Peg A	-	13.12.97 00:27:51	13.12.97 00:41:51	4.55-4.75
51 Peg A	-	13.12.97 00:42:35	13.12.97 00:56:35	4.55-4.75
51 Peg A	-	13.12.97 00:57:17	13.12.97 01:11:17	4.55-4.75
51 Peg A	-	13.12.97 01:12:01	13.12.97 01:26:01	4.55-4.75
51 Peg A	-	13.12.97 01:26:43	13.12.97 01:40:43	4.55-4.75
9 Peg	-	04.05.97 16:13:28	04.05.97 16:22:28	2.38-2.60
9 Peg	-	04.05.97 16:23:10	04.05.97 16:34:38	2.60-3.02
9 Peg	-	04.05.97 16:35:22	04.05.97 16:48:46	3.02-3.52
9 Peg	-	04.05.97 16:49:28	04.05.97 16:55:04	4.55-4.75

* based on ephemeris kindly provided by Geoff Marcy and Didier Queloz

2. Strategy and observations

For our search of an extended exosphere around the planet orbiting 51 Peg, we assume that the planet is a giant gas planet. It therefore should consist mainly of H, He, molecular hydrogen, water and carbon compounds (Atreya 1986). In contrast to Jupiter, where CH_4 is the dominant carbon-bearing molecule, we expect CO to be more abundant as a result of 51 Peg B's higher effective temperature of approximately 1300 K (Guillot et al. 1996; Goukenleuque et al. 1999). Although it is impossible to predict exactly what atoms and molecules to expect, due to the proximity of the star and the resulting efficient photoprocesses, molecules escaping from the atmosphere are likely to be dissociated and ionised quickly. Our search therefore concentrated on dissociation products and ions of the molecules possibly present in the atmosphere of 51 Peg B.

Because of the uncertainty in the molecules present and the extent of dissociation and ionisation, we searched over a wide range of wavelengths to include as many molecular or ionic lines as possible. The ISO Short Wavelength Spectrometer (SWS) was used in mode AOT06 (de Graauw et al. 1996). We covered ranges from 2.39 μm to 3.50 μm and from 4.55 μm to 4.74 μm. These wavelength ranges include a number of atomic lines (e.g. several H-lines, He and He^+ at 4.60 μm and 4.65 μm, respectively) in addition to several molecular bands. For water, its ν_3 band near 2.7 μm is included, in addition to its dissociation (OH near 3.1 μm) and ionisation (e.g. H_2O^+ near 3.08 μm) products. Furthermore, the wavelength ranges cover the neutral

CO v(2-0) band in the range 2.3-2.5 μm and part of the CO v(1-0) band at 4.67 μm. In addition, the CO^+ v(1-0) and v(2-0) bands, centered at 4.58 μm and 2.29 μm, respectively, fall within the observed wavelength ranges. The wavelength range near 3 μm covers molecular bands of NH_3 (ν_1 and ν_3) and its dissociation products NH_2 and NH, as well as the ν_3 band of CH_4 near 3.3 μm. In addition, bands of the H_3^+ ion are present near 3-3.5 μm and near 4.6 μm. The H_2 molecule has several transitions in both wavelength ranges. Thus, the wavelength ranges chosen cover a number of neutral and ionic species which might be present in the atmosphere/exosphere of a large gas giant around 51 Peg.

To detect signatures of an exosphere, we observed 51 Peg during transit phases of its planet. The same observations were then repeated at times when the planet was not in the line-of-sight. Table 1 provides the dates and times of our measurements.

Absorption lines indicative for the presence of a planet may be permanently present in the spectrum of 51 Peg (and independent of orbital phase). Possible scenarios are, for example, material spread along the orbit of the planet (torus-like), or material falling into the star by inward migration (Lin et al. 1996). Such absorption lines can be identified by observations of a comparison star in the same wavelength ranges. The comparison star should ideally be of the same type as 51 Peg, but it should also be relatively bright to keep the amount of observing time reasonable. We have selected 9 Peg (G5Ib), a star of similar spectral type as 51 Peg (G2IV).
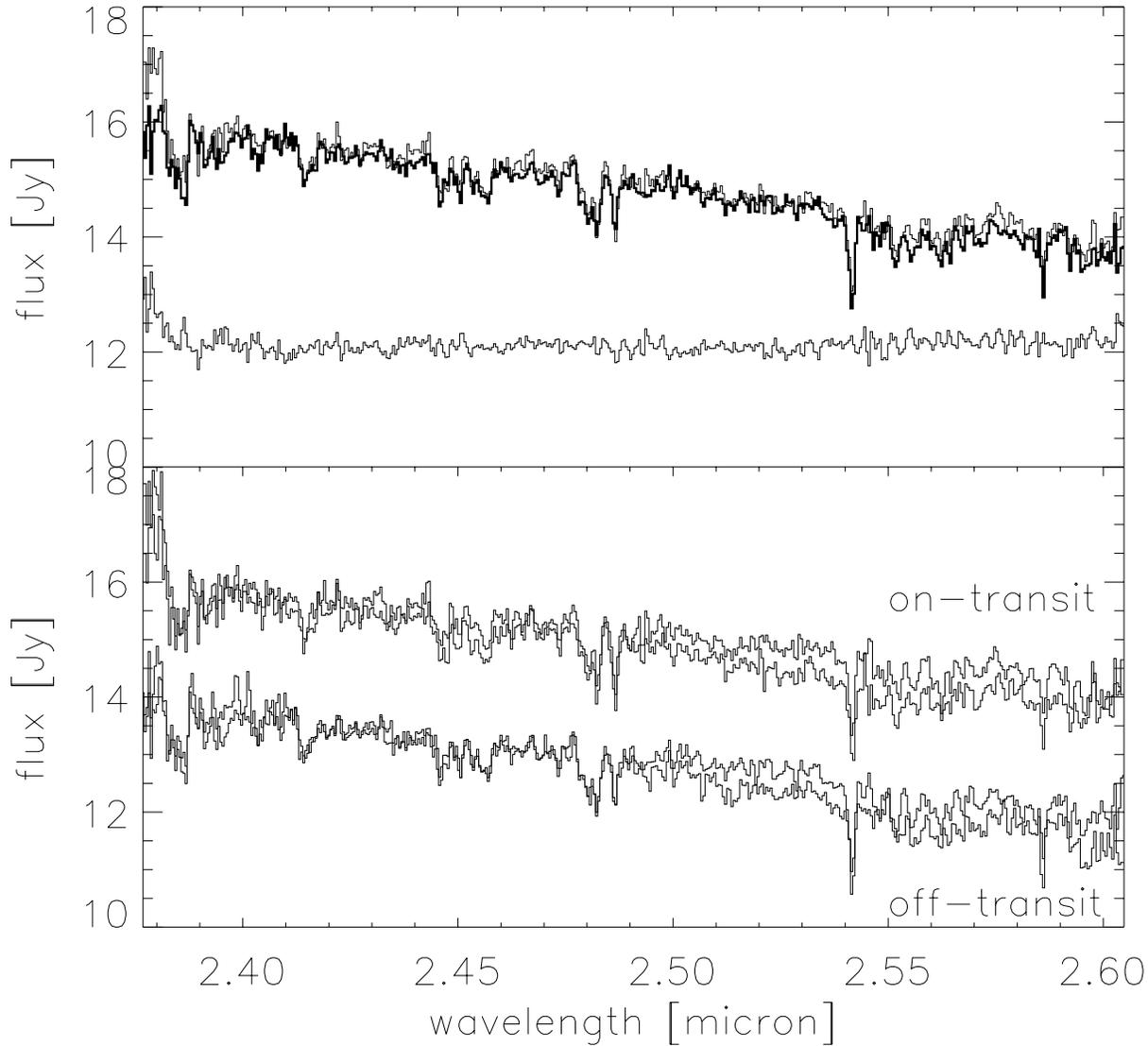
Fig. 1. Top: The on-transit (thin solid line) and off-transit spectrum (bold solid line) are shown (both are combined grating scans). Below, the ratio of both spectra (on-transit/off-transit) is shown to emphasize the differences of the on- and off-transit phases. **Bottom:** For the spectra taken on- and off-transit the individual up and down scans of the SWS grating are overplotted for comparison (the off-transit scans have been offset in intensity to allow a detailed comparison).

3. Search for signatures of an exosphere

The data reduction was carried out using the standard software packages for ISO/SWS reduction and consisted of the normal pipeline procedures in most steps. Inspection of the data recorded at 2.39 μm to 3.50 μm showed the presence of interferences (fringes) in all spectra, which have subsequently been removed by appropriate filtering. However, in some cases, fringe removal was not sufficient and, in particular near the edges of bands, the spectra have a smaller signal/noise ratio than we hoped for. The spectra were rebinned to a resolution of 2500 in the ranges from 2.38-2.60 μm, and to a resolution of 2000, 2500 and 2000 in the ranges of 2.60-3.02 μm, 3.02-3.52 μm and 4.55-4.75 μm, respectively.

SWS records wavelength ranges by scanning the corresponding grating in one direction over the wavelength region of interest, followed by a scan in the reversed direction ('up' and 'down' scans). Both scans are recorded independently and, thus, can be treated as two independent measurements. This aids in detecting the presence of weak features in the spectra, since they must be present in both scans. Instrumental effects which have passed the various reduction steps are unlikely to appear at the same wavelength in both scans. To obtain the best possible signal-to-noise (S/N) ratio, the spectra from both grating scan directions are then combined. In Figs. 1 to 3 the up- and down- scans (bottom part of each figure) and the combined scans (top part) in the range from 2.3 μm to 3.5 μm are shown for times during planet transit (on-transit) and times with the planet not in the line-of-sight (off-transit). To minimize the in-
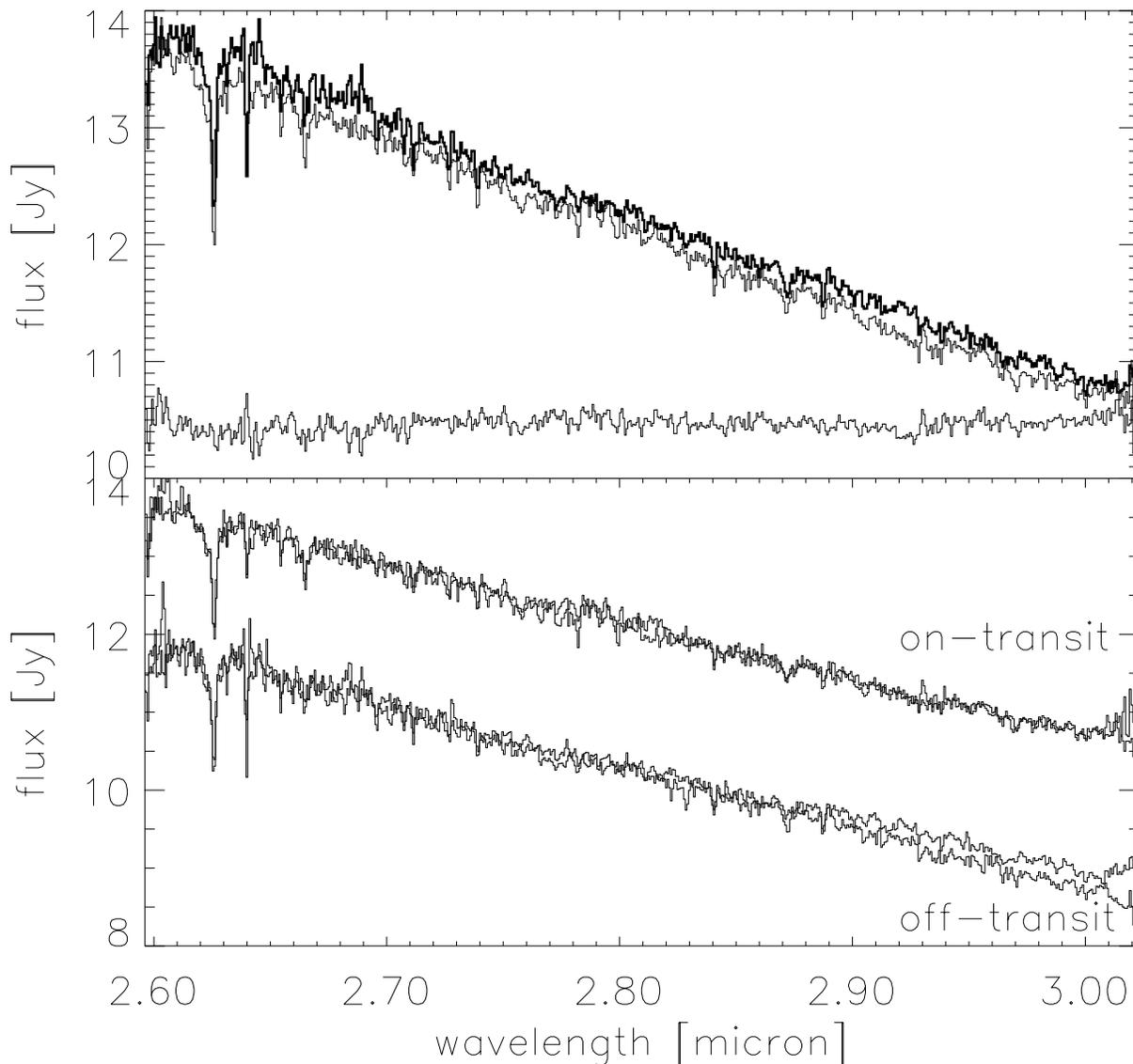
Fig. 2. See Fig. 1.

fluence of additional reduction steps, no attempt has been made to fit and subtract the continuum flux of the star in these figures. Differences in the continuum flux level, when comparing scan directions or on- and off-transit spectra, are due to scanning or pointing effects. However, they do not influence the search for absorption/emission features performed here.

To identify signatures appearing in the spectra during transit phases of the planet orbiting 51 Peg, the combined on- transit spectrum has been divided by the corresponding spectrum taken off-transit (bottom spectrum in top part of Figs. 1 to 3). In general, the S/N-ratio decreases towards the edges in all wavelength bands, and differences between on- and off-transit spectra are therefore less reliable at the edges of the bands. To identify any possible spectroscopic signatures of the transit event, we have used two criteria:

1. A signature must appear in both scans (up- AND down-scan) of the wavelength region.

2. The signature must be outside the local noise level in the original scans and divided spectra.

Criterion 1 removes almost all candidates of transit signatures in our spectra. None of the features appearing as residuals in emission or absorption in the on-/off-transit ratio can be considered real in the range from 2.38 μm to 3.02 μm.

To illustrate how the search for spectral features present during transit phases is performed, we now discuss the wavelength range from 3.0-3.5 μm in more detail. At 3.397 μm and 3.401 μm two stellar absorption features appear in the spectrum taken off-transit (see Fig. 3 and for a better view enlarged in Fig. 4). During transit time, an additional weak absorption line appears at 3.392 μm. In the following, we investigate if this feature could be indicative for absorptions caused by the transit of the planet through the line-of-sight. The additional absorption is present not only in the combined, but also in the individual up and down grating scans obtained during transit. It therefore fulfills
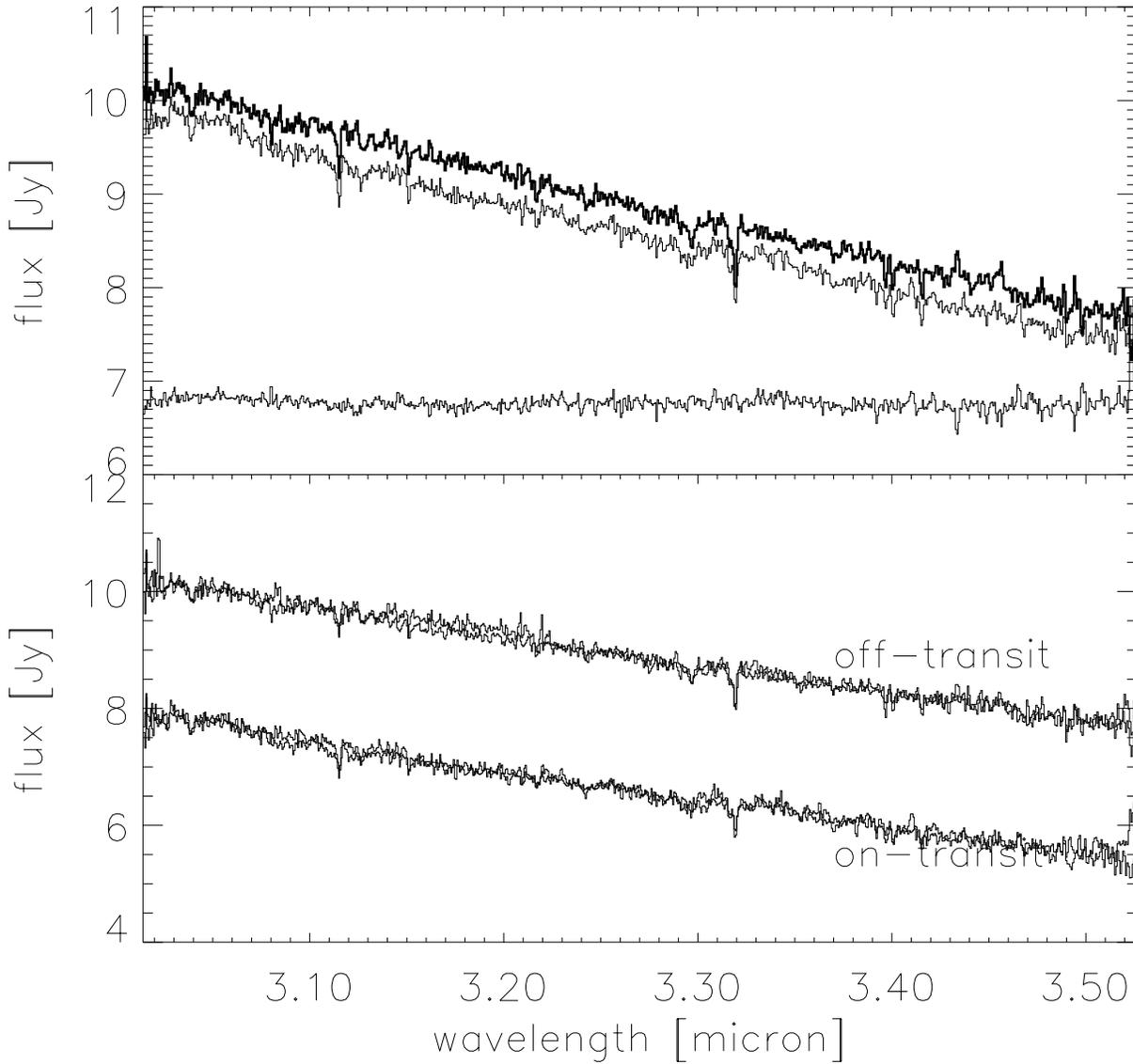
Fig. 3. See Fig. 1.

criterion 1. For comparison, a residual absorption feature in the on-/off transit ratio at 3.434 μm is clearly caused by enhanced noise in one of the off-transit scans and therefore does not agree with criterion 1. To verify if the absorption at 3.392 μm during transit time is a real detection, we calculate its equivalent line width and compare to the noise level (quantitative check for criterion 2). Table 2 provides the signal/noise ratio (S/N) for all bands in a wavelength range near the band center and free of strong stellar absorptions. To determine the noise, the decreasing flux level of the star with wavelength had to be corrected by a polynomial fit to the continuum flux. Table 2 also provides the 3σ upper limit for the detection of an absorption line in each band. The detection limit is expressed by calculating the noise level for the line equivalent width ($I = \int \frac{I_0 - I_\lambda}{I_0} d\lambda$) as: $\sigma_I = \frac{\sigma}{I_0}\sqrt{n}d\lambda$. Here, I_0 is the continuum flux level, σ the noise level of the flux, and n the number of channels (set to 2). The equivalent width of the absorption feature at 3.392 μm

in the combined spectrum taken during transit is $3.2\ 10^{-5}\ \mu$m, thus corresponding to only 4σ (Table 2 and taking into account that it is about 6 channels wide). Similarly, a residual emission feature at 3.465 μm in the 'on-/off-transit' ratio (see Fig. 3) is close to the 3σ noise level. Therefore, for both remnant features our criterion 2 is not sufficiently fulfilled for a secure detection (which should be more than 5σ). Similar arguments can be made for other differences between the spectra recorded during transit phases in comparison with the spectrum of 51 Peg when the planet is not in the line-of-sight.

Figs. 5 to 7 show the spectrum of the star 9 Peg (combined scan) compared with the spectrum of 51 Peg. To increase the S/N ratio for 51 Peg, the spectra taken during and off-transit were averaged. The absorption lines present in 51 Peg appear also in the spectrum of 9 Peg, as expected for stars of similar spectral type. Differences in line strength (for example in the range from 2.38 μm to 2.60 μm, where CO v(2-0) = 2 bands are

Table 2. The signal/noise-ratio, S/N, has been determined in the specified wavelength ranges in each up and down scan spectrum, in addition to the combined scans. The first column indicates the scanning mode and whether the spectrum was taken during (on) or off-transit of the planet. Col. 4: 1σ noise level; I_0: mean flux level in range; $3\sigma_{line}$: 3σ upper limit expected on the equivalent width ($\int \frac{I_0 - I_\lambda}{I_0} d\lambda$) assuming a line width of 2 channels.

| on-/off-transit combined/up/down scan	wavelength range [μm]	S/N	σ [Jy]	I_0 [Jy]	$3\sigma_{line}$ [10^{-5} μm]
on/combined	2.49-2.53	144	0.10	14.8	1.4
on/up	2.49-2.53	127	0.12	14.9	1.6
on/down	2.49-2.53	127	0.12	14.6	1.6
off/combined	2.49-2.53	114	0.13	14.8	1.8
off/up	2.49-2.53	103	0.14	14.6	2.0
off/down	2.49-2.53	111	0.14	14.9	1.8
on/combined	2.75-2.83	159	0.08	12.2	1.7
on/up	2.75-2.83	144	0.08	12.1	1.9
on/down	2.75-2.83	107	0.19	12.2	2.6
off/combined	2.75-2.83	212	0.06	12.3	1.3
off/up	2.75-2.83	156	0.08	12.2	1.8
off/down	2.75-2.83	202	0.06	12.4	1.4
on/combined	3.16-3.26	152	0.06	8.9	1.7
on/up	3.16-3.26	146	0.06	8.9	1.7
on/down	3.16-3.26	105	0.08	8.9	2.4
off/combined	3.16-3.26	148	0.06	9.2	1.7
off/up	3.16-3.26	142	0.06	9.2	1.8
off/down	3.16-3.26	94	0.10	9.2	2.7
on/combined	4.58-4.70	24	0.16	3.9	24.5
on/up	4.58-4.70	25	0.16	4.0	20.6
on/down	4.58-4.70	29	0.13	3.8	27.0
off/combined	4.58-4.70	29	0.15	4.2	18.1
off/up	4.58-4.70	30	0.14	4.1	17.8
off/down	4.58-4.70	28	0.14	4.1	18.4
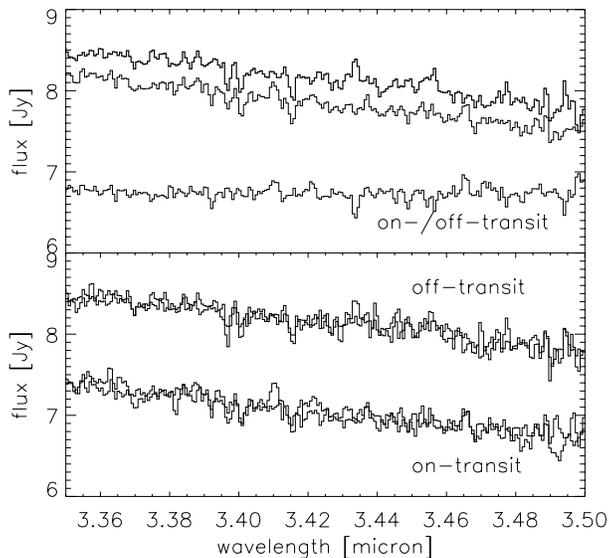
Fig. 4. See Fig. 1.

present) are also expected (comparison of a giant and a solar type star). Near 3.40 μm, the spectrum of 9 Peg is similar to the off-transit spectrum of 51 Peg. In some wavelength ranges (e.g. 2.60-2.90 μm), strong fringes in the spectrum of 9 Peg could not be adequately removed and lead to enhanced 'noise' in the

resulting spectrum. In these ranges, weak absorption features appearing in the spectrum of 51 Peg may vanish within the higher 'noise' in the spectrum of 9 Peg. However, in summary, no clear indication for spectral features appearing solely in 51 Peg, and not in the comparison star, is found.

Figs. 8 and 9 show the spectrum of 51 Peg and 9 Peg in the wavelength range from 4.55-4.75 μm. For 51 Peg, all spectra in this range taken during the transit of the planet have been averaged to increase the S/N ratio. The corresponding off-transit spectra have then been treated in the same way. However, the flux levels in this wavelength range are low and the signal/noise ratio achieved does not allow a search for faint features. Both spectra (on- and off-transit) do not reveal any absorption lines. This is also the case for the comparison star 9 Peg.

4. Summary and discussion

51 Peg was observed to investigate the possible existence of an extended exosphere around its planet. The star was observed during predicted occultations by the planet and at times when the planet was not in the line-of-sight. Spectra have been obtained with SWS in the wavelength ranges 2.39 μm to 3.50 μm and 4.55 μm to 4.74 μm. No clear detections of line features present solely in spectra taken during transit of the planet were found.

A comparison star of similar spectral type (9 Peg) was observed to search for features permanently present in the spec-
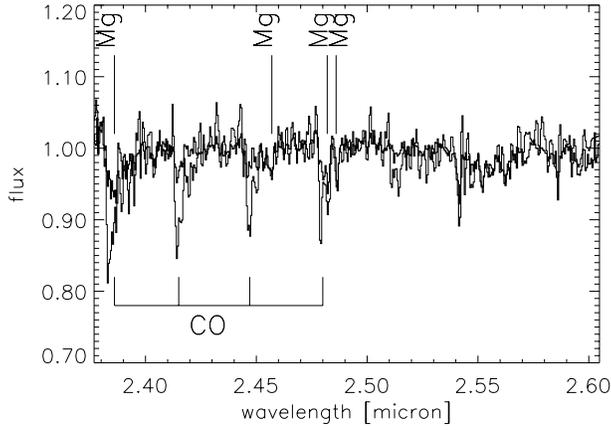
Fig. 5. Spectrum of the comparison star 9 Peg (solid line) and the averaged spectra of 51 Peg (bold line). The continuum flux level has been removed by subtracting a polynomial fit. For some absorption features proposed line identifications are given.
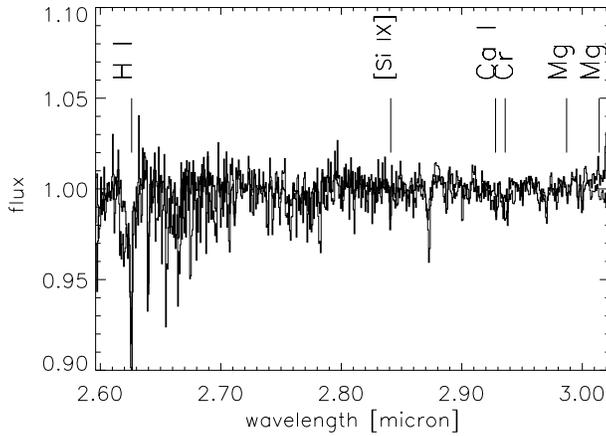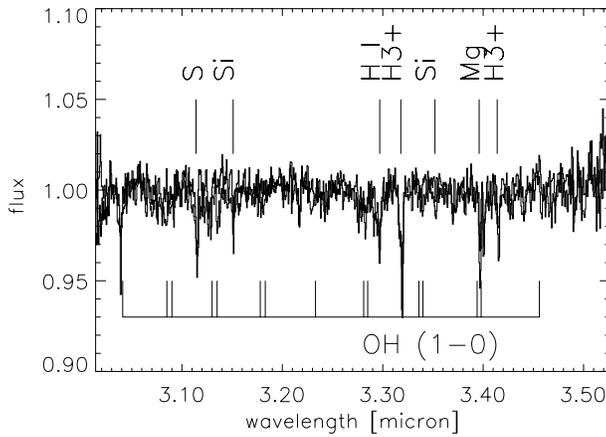

Fig. 6. See Fig. 5

Fig. 7. See Fig. 5

trum of 51 Peg, which might originate from planetary material spread around the star (torus). All absorption lines in the spectrum of 51 Peg (originating from, for example, H, Mg, CO) were also present in 9 Peg, or were too weak to be seen within the higher noise level in 9 Peg caused by fringing. Thus, no indica-
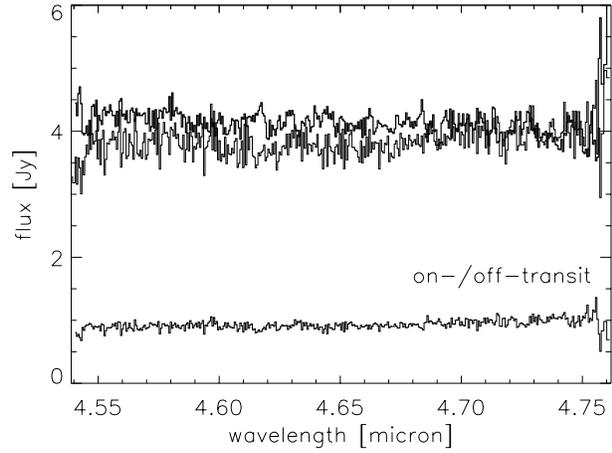

Fig. 8. Spectra of 51 Peg on- (solid line) and off-transit (bold line) (both are combined scans). Below: on-/off-transit ratio.
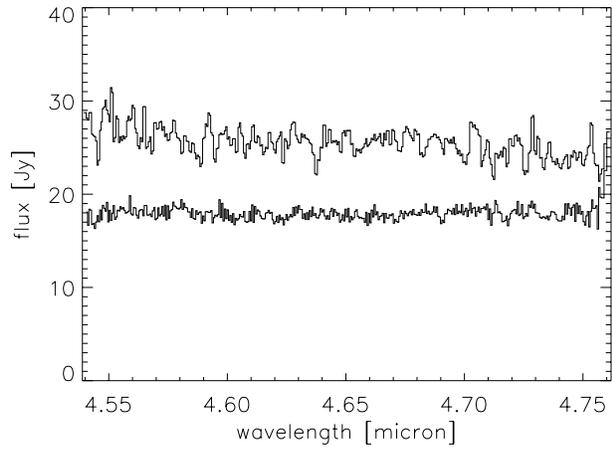

Fig. 9. Spectrum of the comparison star 9 Peg (bold line) and the averaged spectra of 51 Peg (solid line) (scaled by a factor of 5).

tion for absorptions by atoms/molecules of non-stellar material in the line-of-sight has been found by this comparison.

The S/N ratio of our spectra (Table 2) ranged from about 100-200 at 2.39 μm to 3.50 μm. Therefore, absorptions at the 2-4% level should have been detected on a 3σ level. The depth of possible absorptions depends on the temperature and the details of the absorption/emission mechanisms of the molecules in the planetary atmosphere. Quantitative constraints of limits on absorption features caused by the crossing of a potential exosphere of 51 Peg B in front of the star have to be investigated using a detailed atmospheric model in future studies.

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