

## The Search for Extended Atmospheres Around the Planets Orbiting 51 Peg and $\tau$ Boo

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**Abstract.** The stars 51 Peg and  $\tau$  Boo were observed with the high-resolution Utrecht Echelle Spectrograph (UES) on the 4.2-m William Herschel Telescope on La Palma during the times the planets were due to transit in front of them and at times outside of the predicted transit periods. The results of a detailed comparison between on-transit and off-transit spectra to search for signatures of extended planetary atmospheres are presented and discussed. No evidence of transient spectral features correlating with the predicted transit times was found. This project constitutes part of the 1998 La Palma international time program on extrasolar planetary systems.

### 1. Introduction

The stars 51 Peg and  $\tau$  Boo are each supposed to have a massive planet orbiting them (at 0.05 and 0.042 AU, respectively), as inferred from periodic variations in their radial velocities (Mayor & Queloz, 1995; Butler et al. 1997). Relevant stellar and planetary data are given in Table 1. We have attempted to confirm the existence of the planets via detection of atmospheric absorption features during transit of a planet in front of its star.

This project constitutes part of the La Palma International Time Program on planetary systems. The observations were carried out in the visible ( $\sim 3600$  -  $6000 \text{ \AA}$ ) at the WHT with resolutions of around  $0.1$  -  $0.25 \text{ \AA}$ . The dates of the observations were 1998, May 14 - 15 for  $\tau$  Boo (transit prediction: May 14 at 23:01 UT  $\pm$  18 min) and 1998, Oct. 23 - 24 for 51 Peg (transit prediction: Oct. 23 at 20:43 UT  $\pm$  45 min). The transit time predictions were kindly provided by G. W. Marcy. Similar spectroscopic studies have been carried out in the infrared (e.g. Rauer et al. 2000) but so far no evidence for planetary exospheres has been found.

What might we expect to observe? The stars  $\tau$  Boo and 51 Peg are supposed to be accompanied by massive planets of at least 3.9 and 0.47 Jupiter masses,

Table 1. Relevant Stellar/Planet Data

	<b>51 Peg</b>	<b><math>\tau</math> Boo</b>
<b>The stars:</b>		
Distance [pc]	15.4	15.0
Spectral type	G2IV	F7V
Apparent V mag.	5.5	4.5
Teff [K]	5770	6450
RA (2000)	22h 57m 27s	13h 47m 17s
Dec. (2000)	+20°46' 05"	17°27' 22"
<b>The planets:</b>		
Period [days]	4.23	3.31
Semimajor axis [AU]	0.051	0.046
M <sub>sini</sub> [MJup]	0.47	3.87
Inclination of orbit	<85°?	29°?

respectively. We assume these are Jupiter-like gas giant planets. The close proximity of these planets to their stars and the influence of the stellar winds and radiation fields may lead to extended planetary exospheres populated by ions and dissociation products of atmospheric molecules. The planetary exospheres may be drawn out to form comet-like tails which pass through the line-of-sight during transits. Among the possibly relevant species observable in the UES wavelength region are CH, CH<sup>+</sup>, CO<sup>+</sup>, CO<sub>2</sub><sup>+</sup>, H<sub>2</sub>O<sup>+</sup>, and N<sub>2</sub><sup>+</sup>, in addition to atomic species including H, He, and OII.

At the time the observations were carried out it was thought that  $\sin i$  of both stars was sufficiently close to 1 that there was a reasonable chance that the extended exospheres of the planets transit across the stellar disks as seen from the Earth. In the meantime, however, evidence has emerged (Cameron et al. 1999) that the inclination of the orbit of the  $\tau$  Boo planet is only 29°, which would greatly weaken the chances of detecting exospheric absorption lines. In the case of 51 Peg, the results of Henry et al. (1997) suggest the inclination of the planet's orbit is less than 85°.

In both cases transits took place during the first of two nights of observations. We took spectra throughout and after the transit period (lasting an estimated  $\sim 3$  hr in both cases) to follow the development and disappearance of absorption lines as the planets passed in front of their stars. In each case similar sequences of reference spectra were taken on the second night.

## 2. Observations and Data Extraction

A total of 62 spectra of  $\tau$  Boo, each with an integration time of around 100 s, were taken in the period 1998 May 14, 21:30 - 04:50 UT. Batches of five  $\tau$  Boo spectra were interspersed with arc, sky and occasional comparison star exposures. The predicted transit mid-point for  $\tau$  Boo was at 23:01 UT, with an expected duration of about 3 hr. A similar (reference) sequence was taken on May 15.

A total of 48 spectra of 51 Peg, each with an integration time of around 300 s, were taken in the period 1998 October 23, 19:00 - 03:00 UT. The observation sequence was similar to that for  $\tau$  Boo. The predicted transit mid-point for 51 Peg was at 20:43 UT, with an expected duration of about 3 hr. A similar (reference) sequence was taken on October 24.

The data were extracted at St Andrews University using an automated pipeline reduction system built around the Starlink ECHOMOP and FIGARO packages. At the start of each night, median bias and flat-field frames were computed from 20 to 30 frames each, taken on the afternoon prior to the observations.

The initial tracing of the echelle orders on the CCD frames was performed manually on the spectrum of the B star  $\eta$  Hya, which was observed at the beginning or end of each night. The automated extraction procedure then subtracted the bias from each frame, cropped the frame, determined the form and location of the stellar profile on each image relative to the trace, subtracted a polynomial fit to the scattered-light background in the inter-order gaps, and performed a simple (un-weighted) extraction of the orders, applying flat-field balance factors in the process.

Wavelength calibration was performed using a 4-coefficient (cubic) polynomial fit to the wavelengths of lines identified in thorium-argon arc comparison spectra. In the case of  $\tau$  Boo the full width at half maximum intensity of the thorium-argon lines in the arc calibration spectra was 2.1 pixels, giving an effective resolving power  $R = 48900$ . In all, 62 orders were extracted from each frame, giving full spectral coverage from 3640 to 6120 Å. The corresponding figures in the case of 51 Peg are 2.3 pixels,  $R = 43500$  and 3617 to 6054 Å. There is considerable wavelength overlap between adjacent orders.

### 3. Data Analysis and Results

For each star all spectra taken within a 2-hr period centered on the predicted transit mid-point were corrected for small relative wavelength shifts and averaged (a total of  $\sim 13$  spectra). A corresponding mean spectrum from the same UT interval on the following night (off transit) was used as a reference. A detailed comparison of the on-transit and off-transit mean spectra was made for each of the 62 orders. The example shown in Fig. 1 (left-hand frame) is the  $H_\beta$  line of 51 Peg around 4861 Å. The plotted spectrum is the on-transit mean spectrum from 1998 October 23 (thin line) superimposed on the mean reference (off-transit) spectrum from 1998 October 24 (thick line). However, the two spectra are virtually indistinguishable and no differences are discernible. Plotted above in the same frame, multiplied by an arbitrary amount, is the ratio of the on-transit mean spectrum to the off-transit mean spectrum, with  $1\sigma$  error bars. Small dips in the ratio plot correspond to strong narrow lines and are due to slight sampling differences between the on-transit and off-transit spectra. The maximum sensitivity of the ratio plot to transit-related absorption features can be estimated on the basis of the variance in the range 4860 to 4863 Å, in which there is little interference from strong narrow lines. The resulting signal/noise ratio is 428 which, given  $R = 43500$ , implies a minimum detectable equivalent width at the  $3\sigma$  level of 0.8 mÅ.

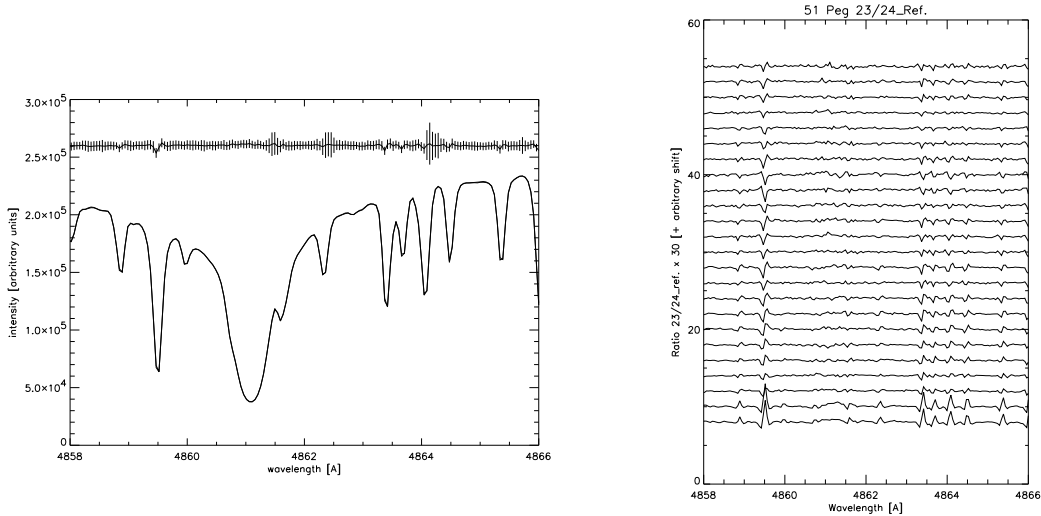


Figure 1. The  $H_{\beta}$  line of 51 Peg. Left frame: the on-transit mean spectrum from 1998 October 23 (thin line) is plotted over the mean reference (off-transit) spectrum from 1998 October 24 (thick line). (The two spectra are indistinguishable in this figure.) The upper plot is the ratio of the on-transit mean spectrum to the off-transit mean spectrum, multiplied by an arbitrary amount, with  $1\sigma$  error bars. Right frame: successive individual on-transit spectra taken over a time interval of 3.5 hr, centered on the predicted time of mid-transit, divided by the corresponding order in the mean off-transit reference spectrum from 1998 October 24. Time increases downwards.

In order to monitor the development of features during the course of the transit, the ratios of selected orders of successive individual on-transit spectra taken over a time interval of 3.5 hr, covering the predicted UT interval of the transit, to corresponding orders in the mean off-transit reference spectrum from 1998 October 24, were plotted in a sequence. As an example the sequence containing the  $H_{\beta}$  line of 51 Peg is shown in Fig. 1, right-hand frame. Time increases downwards and the 12th plot corresponds to the time predicted for mid-transit. The time interval between successive plots is about 9 minutes. The dips in the ratio plot of the left-hand frame, due to the aforementioned sampling differences, stand out clearly in the sequence frame but no time-dependent features attributable to the passage of the planetary exosphere across 51 Peg are evident. Nevertheless, it is clear that this type of sequence frame is a very useful and sensitive tool for the purposes of searching for weak time-dependent features in a large volume of spectral data.

The fact that there is considerable overlap in the wavelength coverage of adjacent echelle orders allowed many candidate features to be dismissed immediately as spurious by comparison of the same wavelength regions in different orders.

In the region around the Na D lines a number of apparently significant absorption enhancements are evident in the mean on-transit spectrum (Fig. 2, left-hand frame), in particular in the range 5898 - 5902 Å. Furthermore, the corresponding sequence frame (Fig. 2, right-hand frame) shows that these

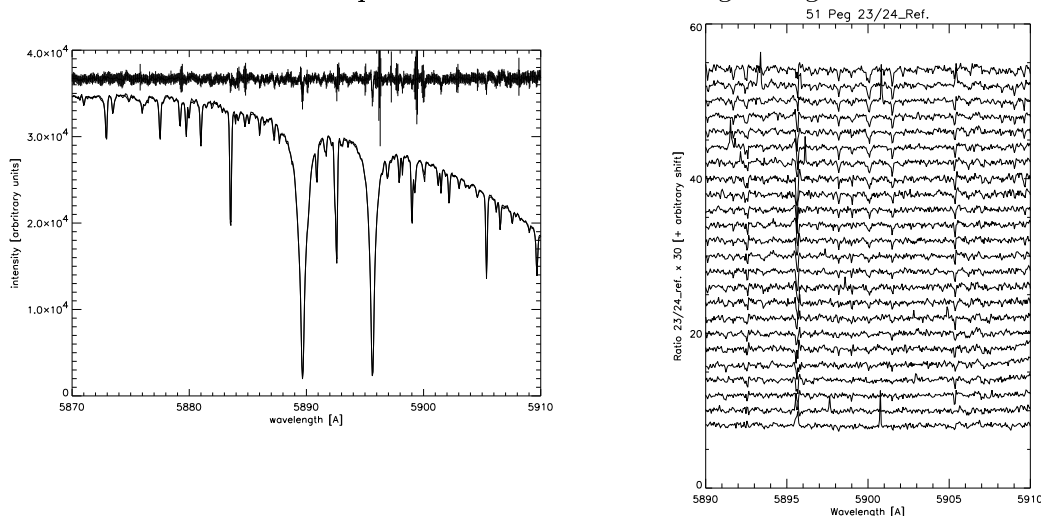


Figure 2. The Na D lines of 51 Peg. Details as in the caption to Fig. 1.

features appear to decrease in strength during the course of the transit. However, exactly the same features appear in the case of  $\tau$  Boo, but enhanced in the *off-transit* reference spectrum, and also in the comparison star spectra, which demonstrates conclusively that they are telluric lines.

The maximum signal/noise ratio of the on-transit mean/off-transit mean order ratios is around 500. With a representative resolution interval of 0.15 Å the minimum ( $3\sigma$ ) detectable equivalent width is around 1 mÅ.

#### 4. Conclusion

Detailed comparison of on-transit and off-transit spectra of the 51 Peg and  $\tau$  Boo systems has revealed no evidence of transient spectral absorption features arising from the passage of extended planetary exospheres in front of the stars. The maximum sensitivity of this study is around 1 mÅ.

#### References

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