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Line profile variation and planets around 51 Pegasi and υ Andromedae*

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Abstract. We report results of high resolution spectroscopic observations of the stars 51 Peg and υ And. Variations in the shape of different lines are studied in the light of a recent controversy concerning the existence of a planet orbiting around 51 Peg. Bisector variations have been noticed for both stars, their shapes and variations are not easily understood, but they do not indicate any interpretation differing from the now classical interpretation by a planet.

Key words: techniques: radial velocities – techniques: spectroscopic – planets and satellites: general – stars: individual: 51 Peg – stars: individual: υ And

1. Introduction

The announcement in October 1995 by Mayor & Queloz (1996) of the discovery of a Jupiter-mass object orbiting around the solar-type star 51 Peg (HR 8724), opened a new era in the history of the planetary astronomy. Their measurements were made (Mayor & Queloz 1995) with the fiber-fed echelle spectrograph ELODIE of the Observatoire de Haute-Provence, France. This instrument allows radial velocity accuracies of about 13 m s^{-1} of stars up to 9 mag in a exposure time $\leq 30\,mn$. The first object showing a clear signature of a periodic radial velocity variation was 51 Peg. From their measurements, they concluded to the presence of a companion with a minimum mass of 0.5 M_J orbiting at a distance of 0.05 AU from the star, with a period of 4.23 d and a half-amplitude of the velocity variation of 59 $\pm$ 3 m s^{-1}. Confirmations of these observations appeared soon (Mayor et al. 1995, Marcy et al. 1997) and several planet candidates were proposed from measurements using slightly different techniques, providing errors as small as 3 m s^{-1} (Butler & Marcy 1996, Marcy & Butler 1996, Butler et al. 1997) among them 47 UMa, 55 Cnc, τ Boo, 70 Vir and υ And.

However, Gray (1997) and Gray & Hatzes (1997) analysed the Fe I line at 625.257 nm in 51 Peg, finding a variation of the shape of the line bisector with a period of 4.23 day. As the planet hypothesis cannot account for implicit variations of the spectral line profiles, they claimed that the planet hypothesis was no longer viable but that the radial velocity variations were due to non-radial pulsations in the star.

Mayor & Queloz (1995) did not find any significant variation of the shape of the bisector of the MEAN profile of the absorption lines.

It was rather clear that new observations dedicated to the variations of the line shapes in 51 Peg were useful. We applied for telescope time, in order to observe 51 Peg on the one hand, and on the other hand a star with a larger velocity variation: υ And, and we present here the results of these observations.

In the mean time, Gray himself (1998) noted that the variation of line profiles are hardly larger than the measurement errors, and therefore are no more considered as significant. Moreover, in the higher spectral resolution measurements of Hatzes et al. (1997, 1998), the variations of shapes are also found small.

Brown et al. (1998) observed the profile of 51 Peg lines with a resolving power R = 50000, analysed the shape of the bisector of the mean profile (about 60 lines) by a Hermite polynomial and found no significant shape variations.

2. New observations

Four nights were allocated in October 1997, at the 3.6m CFHT telescope in Hawaii. Our working strategy was to follow the line bisector variations of some unblended lines with a low Landé factor in the list of Soderblom (1982), with different equivalent widths and different excitation potentials. As it was not possible to get all these lines in one frame, we had to move the grating to get to the right wavelength position. This operation did not require to enter in the spectrograph room. In order to ensure the best accuracy, we took calibration frames before and after each scientific exposure. Due to bad weather conditions at the beginning of the first night, we could observe 51 Peg only during 3 nights. High resolution spectra were obtained with the Gecko spectrograph. The detector was a Lesser-thinned, two-side-buttable Loral CCD 2kx2k with a pixel size of 15 μm. For both stars, we took spectra centered on the two FeI lines at 652.2 nm, 643.0 and on the NiI line at 664.3 nm.

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* based on observations carried out at the Canada-France-Hawaii Telescope

Table 1. Velocity span, velocity curvature and radial velocity for 51 Peg expressed in m s^{-1}

phase	$line$	$Vel.Span$	$Vel.Curv.$	Vr
0.73	625.2	12.6	0.3	−55.
0.96	625.2	−6.3	16.4	+14.
0.20	625.2	0.5	13.8	+53.
0.73	643.0	1.6	7.8	−55.
0.96	643.0	12.3	4.6	+14.
0.20	643.0	−39.	37.0	+53.
0.73	664.3	−114	125.	−55.
0.96	664.3	−160	147.	+14.
0.20	664.3	−154	148.	+53.

The resolution was around 110 000 measured on the thorium lines and the S/N in excess of 500 for each spectrum. For each line, we took 2 to 3 spectra from which we computed the line bisector. The data have been reduced with the software package ASRETI from the Spite group. This package includes the standard flatfielding, wavelength calibration and optimal extraction routines. The bisectors are computed following Gray (1988).

3. Results about 51 Pegasi

Figs. 1 to 3 show the variations of the bisectors for 3 lines taken in the spectra of 51 Peg. For each bisector, we have computed the values of the bisector span (Gray 1998) and the bisector curvature (Gray 1997). The results are gathered in Table 1. The Ni line at 664.3 nm shows a very different shape with respect to the two Fe I lines. The reason is that the two (strong) Fe lines are formed in higher layers than the fainter Ni line. The examination of the figures suggests that the shapes of the bisectors of the same spectral line measured at different phases are sometimes really different. The accuracy of the measurements, computed with the method of Gray (1988) is found to be around one sigma = 15 m s^{-1} (this is an internal error). The drawings 1 to 3 gather the measurements made on each observed profile, NOT on the average of the several profiles observed at about the same date. It is therefore possible to have an independent evaluation of the precision of the measurements. The agreement of the independent measurements is often excellent, confirming in this way the reality of the variation of the shape of the bisector from one night to the following one. The Table 1 shows then that a significant (2 sigma or more) variation in the parameters of the shape of the bisector is sometimes apparent: for instance a jump is noticed in the value of the span and curvature between phases 0.96 and 0.20 for the Fe line at 643.0 nm, and a jump in the span between phases 0.73 and 0.96 for the Ni line. In order to get an easier comparison with the discussion of Gray & Hatzes (1997), the origin of the phase is chosen here at the maximum of the radial velocity.

In a way, these results show that, at least at the time of the observations, (October 1997) there is some variation in the shape of the bisector, as found by Gray (1997), somewhat larger than those found in the November 1995 observations of Hatzes et al. (1997).

However these results do not support the interpretation of the radial velocity variation by non-radial pulsations. Qualitatively, the curvature of the bisector versus phase does not follow the pattern shown by the model of Gray & Hatzes (1997). For example the variation of curvature observed in the Fig. 2 (Fe I line at 634 nm) from phase 0.20 to phase 0.96 is the opposite of the variation predicted by the model of Gray & Hatzes (1997). A similar opposition of phase is also noted by Hatzes et al. (1998) but for the Fe I line at 625nm, observed on July-September 1997. In our observations (October 1997), the bisector curvature of this particular line could be said, on the contrary, to agree with the model, but the bisector shape variation of this line at 625.2 nm

– is very small (the agreement is not very convincing)
– is smaller than the variation of the two other lines, including the other very similar iron line
– is not in phase with the variations of the other lines. Even the small difference of the formation depth, which may exist for the two iron lines, despite very similar equivalent widths and very similar excitation potentials, is a factor important enough for changing the behaviour of the bisector, suggesting that this variation is not predominantly governed by the global velocity field of a pulsation. Summarising, the variations of bisector shape, advocated by Gray (1997) and Gray & Hatzes (1997) are probably real, but are weak, at the limit of measurement errors, and do not conform to the model predictions.

Our result is a confirmation of the 2 recent studies of Gray (1998) and Hatzes et al. (1998). The measurements made by Hatzes et al. are based on very high resolution spectra (R=200,000). These observations were made on 18 nights spanning the time period 1997 July – 1997 September. They also concluded that a planetary companion remains as the only viable explanation for the observed radial velocity variations. Our study, although based on a more modest data set shows the same effect of having bisectors which are different from one line to the other. Let us note that the paper of Hatzes et al. (1998) shows clearly that the bisector variations disappear when the profile is the mean of a few line profiles. Mayor & Queloz (1995) and Brown et al. (1998) did not find significant variations of the bisector shape in the *mean* profile of numerous lines, and it would be interesting to try to find the shape of the bisectors of mean profiles obtained by averaging (cross-correlating) separately the profiles of some groups of individual lines formed at very similar depths (equivalent widths and excitation potentials as similar as possible).

Finally, our observations of 51 Peg confirm that SMALL variations of shape of line profile seem to occur, but these variations

– are not in phase from one line to the other
– are not in phase with the variations of radial velocity
– and are not in agreement with the predictions of the model of Gray & Hatzes (1997) leading to the conclusion that pul-

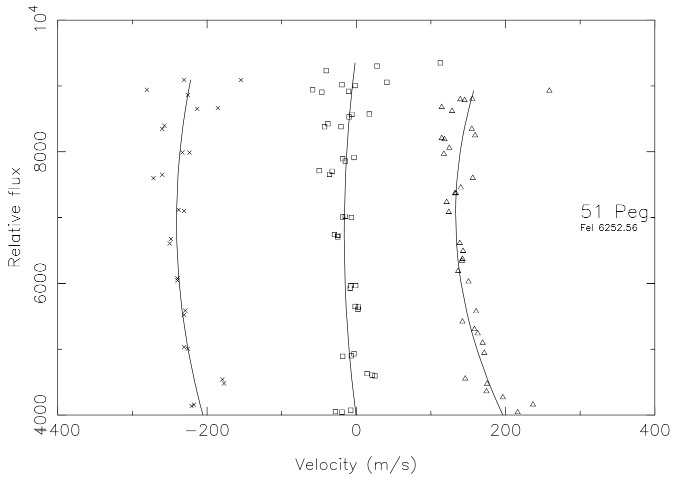

Fig. 1. 51 Peg: bisectors of the Fe I line at 625.2 nm for the 3 nights (3 phases). Crosses: ϕ=0.73 shifted by -200 m s^{-1}, squares: ϕ=0.96, triangles: ϕ=0.20 shifted by +200 m s^{-1}. Solid lines represent polynomial fits.

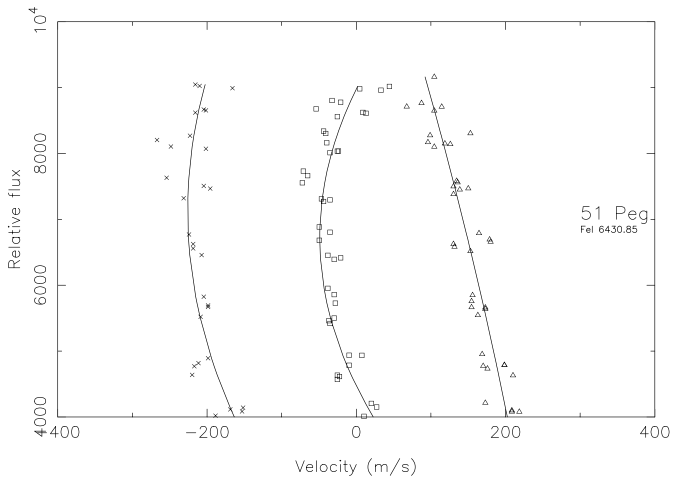

Fig. 2. 51 Peg: bisectors of the Fe I line at 643.0 nm for the 3 nights. Symbols are the same as in Fig. 1. The curvatures of the lines vary with the phase in a way contrary to the predictions of Gray & Hatzes (1997).

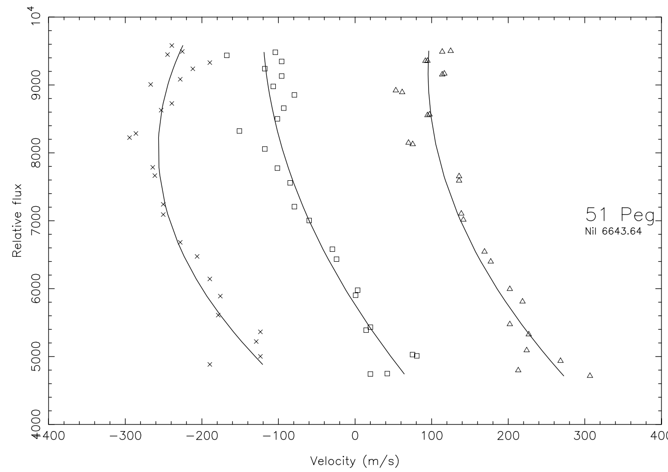

Fig. 3. 51 Peg: Bisectors of the Ni I line at 664.3 nm for 3 consecutive nights. The symbols are the same as in Fig. 1. At the same phase, the velocity spans of the Ni I line are different from the ones of the Fe I lines (note the different velocity scale of the drawing).

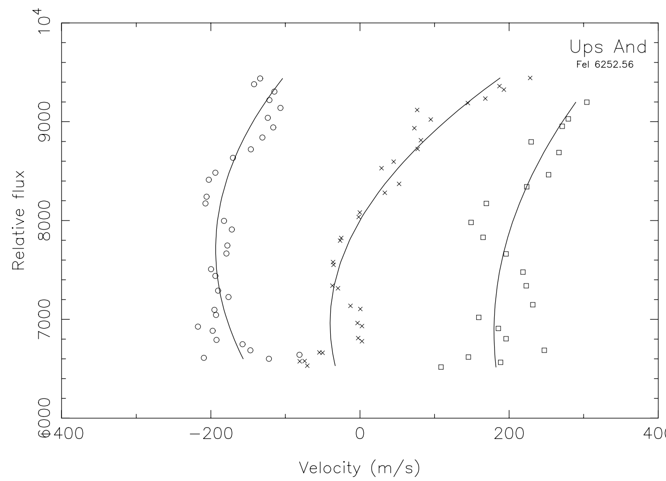

Fig. 4. υ And: bisectors of the Fe I line at 625.2 nm. Circles: ϕ=0.39 shifted by -200 m s^{-1}, crosses: ϕ=0.59, squares: ϕ=0.79 shifted by +200 m s^{-1}. Solid lines represent polynomial fits. The lines of υ And have bisector shapes clearly different from those of 51 Peg. The measurements are not tightly gathered around the mean curve.

sations of high order are ruled out. Since the excitation of a single (low) order is unlikely, the observations confirm that the planet hypothesis is the best explanation for the observed velocity variations in 51 Peg.

4. Results about υ Andromedae

The radial velocity monitoring of υ And (HR 458) (Butler et al. 1997) has shown that this star exhibited Keplerian velocity variations, with a period (4.61 d) rather similar to the period found for 51 Peg, and an amplitude of 74 m s^{-1}, consistent with an orbiting " 51 Pegasi-type" planet. Very recently, follow-up observations (Marcy et al. 1999) confirm this periodicity and reveal additional periodicities. Marcy et al. (1999) claimed that their observations imply a system of 3 massive planets orbiting around υ And. The star is the primary component in a visual double star system: it has been noted as a spectroscopic binary, but further analyses discarded this binarity (Morbey & Griffin 1987, Duquennoy & Mayor 1991, McAlister et al. 1992) This star is located just above the main sequence. Its F8V spectral type implies that the metallic lines are weaker and requires a longer observing time (a better S/N) to get precise bisector variations measurements. We followed the bisector variations during 3 consecutive nights (for the line at 625 nm) and 4 nights (for the line at 643 nm) which cover almost a complete period.

Figs. 4 and 5 show the line bisector variations for the 2 Fe I lines. The Ni I 664.3 nm line was too weak to provide interesting results. A comparison of the shape of the bisectors shows a stronger curvature than the one found for 51 Peg. This phenomenon is well known and described in detail by Gray (1988).

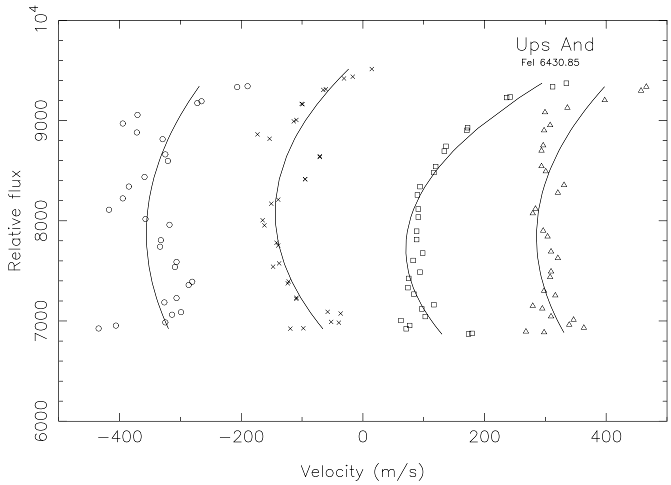

Fig. 5. υ And: bisectors of the Fe I line at 643.0 nm. Circles: ϕ=0.39 shifted by -300 m s^{-1}, crosses: ϕ=0.59 shifted by -100 m s^{-1}, squares: ϕ=0.79 shifted by +100 m s^{-1}, triangles: ϕ=0.05 shifted by 300 m s^{-1}. Solid lines represent polynomial fits. The precision of the measurements is illustrated by the fact that, often, two successive spectra provide very close measurement points on the drawing, even if the two close points are both far from the mean curve.

Table 2. Velocity span, velocity curvature and radial velocity for υ And expressed in m s^{-1}

phase	$line$	$Vel.Span$	$Vel.Curv.$	Vr
0.39	625.2	39	23	47
0.59	625.2	153	−20	−27.3
0.79	625.2	90	−14	−73.9
0.39	643.0	27	43	47
0.59	643.0	−6.	83	−27.3
0.79	643.0	104	67	−73.9
0.05	643.0	40	50	22.9

In Table 2 are reported the measured values of the velocity span and the velocity curvature of the bisectors of the two lines. However, the definitions have been modified because the lines are weaker than in 51 Peg: they have normalised central depths around 0.7. We adopted, for measuring the velocity span, the depths 0.71 and 0.9 and for the velocity curvature the depths 0.71, 0.85 and 0.9. For υ And, the variations of the bisector are stronger than those found for 51 Peg, but the uncertainties are also larger: the measured bisector seems less smooth and less similar to a second order polynomial. However the span jump of the line at 625 nm reaches 113 m s^{-1} (and the curvature jump reaches 43 m s^{-1}) between the phases 0.39 and 0.59. Also the span jump reaches 110 m s^{-1} between the phases 0.59 and 0.79, (and there is a curvature jump reaching 40 m s^{-1} between phases 0.39 and 0.59). It can be concluded that shape variations occur. But, although the limited observing time does not enable to cover a full period, no sign of a systematic variation of shape with phase is apparent. The amplitudes of the variation are different for the two similar Fe I lines. And again, the shape variation which appears at one phase in the first Fe I line, appears at another phase in the second Fe I line. Therefore, also in υ And, the observations do not favour the explanation of the radial velocity variation by pulsations.

The precision of the bisector measurements for υ And is similar to the precision obtained for 51 Peg, i. e. 15 m s $^{-1}$ as indicated in Sect. 3. Moreover, the coherence of the independent measurements is very often excellent as apparent on the Figs. 4 and 5 (indeed two independent measurements are sometimes virtually identical). This coherence is a confirmation of the evaluation of the precision of the measurements. The deviations and irregularities observed on some of the bisectors seem to be real, but if real, their interpretation is not obvious. The data about bisectors published in the literature are usually the shapes of the mean bisectors of a few lines (time averages), although the individual bisectors are widely different (see e.g. Gray et al. 1996a, 1996b) We display here the individual measurements. In the case of 51 Peg, Mayor & Queloz (1995) showed that it was not possible to explain the radial velocity shift by radial pulsations nor multiple spots. But this does not imply that 51 Peg is completely deprived from the smallest spots or weak oscillations. Similarly, precise observations of υ And could reveal minute phenomena, unable by themselves to account for the velocity shift, but leaving some imprint on the shape of the bisectors. The presence of 3 planets orbiting around υ And implies multiperiodic radial velocity variations. However, these 2 newly discovered planets cannot explain the bisector variation we measured for 2 main reasons:

- The periods associated to the 2 new planets, namely 242 and 1269 days, are not of the same order of magnitude as the timescale of variation of the bisectors.
- The bisectors variations differ from one line to the other

5. Discussion

The distortion of the bisector can have, in addition to physical phenomena associated with the stellar atmosphere, two origins associated with the presence of the planet. As first suggested by Bruston (1992), the stellar light reflected by the planet mixes the spectrum of the star with that of the planet; but, as calculated in more details by Charbonneau et al. (1998), this reflection affects only the upper part of the spectral line (near the continuum). A more important effect is due to the ‘cometary tail’ necessary present for giant planets in close orbit (Schneider et al. 1997): the stellar spectrum is perturbed by absorptions in the tail, whose Doppler shift can be up to hundreds of km s^{-1}. This latter effect takes place only if the inclination of the orbital plane of the planet is not too far from 90$^{\rm o}$; the probability of such an event is $R_T/R_* \sim 20\%$ (R_T being the transverse size of the tail). This explanation suffers from the fact that, as physical conditions in the cometary tails are very different from what exists in stellar atmospheres, it is very unprobable that the cometary lines interfere with our observed lines.

Saar & Donahue (1997) studied the contribution to v_r from the activity related sources, starspots and convective inhomogeneities, as these features rotate across the disk and evolve in time.

For 51 Peg, their analysis shows that a photometric stability better than 0.0002 mag rules out any effect on the velocity span which could come from starspots. However, they also found that variations induced by nonuniform convection can lead to an effect as high as 10 m s^{-1}.

υAnd has a rather high $vsini$ (about 9.4 km s^{-1}) with respect to 51Peg (2.1 to 2.4 km s^{-1} according to different authors: see François et al. (1996), Gonzalez (1998). Their computations show that effects of nonuniform convection for a star with a similar $vsini$ like χ^1Ori may have variations of the velocity span of the order of 100 m s^{-1}. The velocity span variations we measured for our 2 stars could well be explained by this phenomenon.

However, in order to disentangle effects intrinsic to the star from effects induced by the planet, it would be of importance to make similar measurements for stars with no known planet

Finally, the best explanation for the observed velocity variations resides in the presence of planets orbiting around the star, not excluding additional side effects.

6. Conclusion

We have performed high resolution, high signal to noise ratio observations of the stars 51 Peg and υ And at the CFHT, Hawaii on October 1997. These observations have been used to determine the bisector variations of some unblended lines. For both stars, we observed a variation of the shape of the bisector of two or three neutral lines. The observed variation of the shape of the bisector is slightly at contrast with the observations of other lines in the spectrum of 51 Pegasi on November 1995 by Hatzes et al. (1997) who found that the variations are smaller than the measurement errors. Real variations of the bisector could favour the interpretation by stellar pulsations, however, the variation of the bisector is not coherent with the predictions of the model of Gray & Hatzes (1997).The line at 625 nm is sometimes in phase opposition with the model (observations of Hatzes et al. 1998 on July-September 1997), sometimes not (our observations, October 1997). The curvature of the line at 643nm is in phase opposition with the model (our observations, October 1997).

Moreover, the shape variations are not in phase from one line to the other. For the weaker Ni I line, the phase difference could be attributed to a significantly different formation depth in the stellar atmosphere. However, it is not the case for the 2 very similar iron lines, where also the variations of the bisector are not similar and are not in phase. This difference of behaviour in similar lines suggests that the small variations of the bisector shape are not dominated by a global stellar pulsation, but rather by local effects. The very limited amplitude of the variations of the bisector shape rules out pulsations of high order, but then the excitation of a single low order is very unlikely. The observed Doppler velocity variations are therefore best explained by the existence of planets orbiting around these stars.

As a conclusion, we would like to mention that this work shows that in addition to a variation of bisector shapes with the depth of formation of the lines (a well known fact), the *variation* of this bisector shape varies strongly with, presumably, line formation depth. It would therefore be interesting to use existing spectral data on 51 Peg and υ And, averaging (cross correlating) separately some groups of lines, all formed at closely similar depths, in order to reach the most accurate determination of the mean bisector shape at different depths, and get in this way some information about its origin.

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