Long-term High-resolution Spectroscopy of γ Cas, ζ Tau, and π Aqr.

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Abstract

High-resolution spectroscopic data ($\lambda\lambda$ 5285–6595 Å) for three bright classical Be stars with unusual Hα profiles (γ Cas, ζ Tau, and π Aqr) have been obtained from 1993–2000 at the Ritter Observatory of the University of Toledo. The data for γ Cas are supplemented by medium-resolution spectroscopy taken at the Terskol station of the Main Astronomical Observatory of the Ukranian Academy of Sciences. The stars show the presence of an additional variable (central) emission peak in the Hα line, which has a double-peaked profile in most stars of this type. Long–term radial velocity (RV) variations of H I, He I, Si II, and Fe II lines are detected in γ Cas and ζ Tau. The RV of the central peak of Hα in ζ Tau seems to follow the binary orbital motion (period 132.9 days) on top of the long-term variations (period 1518 days). In γ Cas this peak shows a constant trend towards negative velocities since 1993, which is opposite to the behavior of other emission lines. Short-term RV variations of the Hα emission peak with a period 84 days are found in π Aqr during its weak-disk phase (since 1996).

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Introduction

Classical Be stars are known to display spectral line profile variations on different time scales. Although bright Be stars have been rather frequently observed for more than a century, the bulk of spectroscopic results were obtained either non-regularly or at low and medium resolution. Furthermore, in most studies only the emission lines receive researchers' attention. Here we report the results of our long-term high-resolution spectroscopy of three bright ($2 \leq V \leq 5$ mag.) Be stars, γ Cas, ζ Tau, and π Aqr.

A large number of Be stars are binary systems, probably undergoing mass exchange. Our targets were chosen because of their unusual Hα profile shape, which frequently contains a variable central peak in addition to the double-peaked structure seen in almost all Be stars. This fact may be connected with their binary nature. In fact, ζ Tau is known as a single-lined binary with a 132.9-day period (e.g., Harmanec 1984), while γ Cas is a suspected binary with a compact secondary component (Haberl 1995). π Aqr did not show any evidence for binarity before its recent weak-disk phase (since 1996).

Observations and Data Reduction

High–resolution spectroscopic observations were obtained from 1993–2000 at Ritter Observatory of the University of Toledo, using a 1 m telescope equipped with a Wright Instruments Ltd. CCD camera in a fiberfed échelle spectrograph. The spectra, covering the wavelength range 5285 to 6597 Å, consisted of nine non-overlapping $\simeq$ 70 Å wide orders, with spectral resolving power R $\simeq$ 26 000. The Ritter data were reduced with IRAF version 2.10.3β[1]. In total, 81 spectra were acquired for ζ Tau (August 1991 – March 2000), 72 for γ Cas (November 1993 – March 2000), and 65 for π Aqr (May 1996 – December 1999).

Medium–resolution (R $\simeq$ 6500) photographic spectroscopy of γ Cas in the Hα line region was taken in 1987–1988 at the 60 cm telescope of the Terskol station of the Main Astronomical Observatory of the Ukrainian National Academy of Sciences.

Radial velocities (RV) were measured by fitting line profiles (or their parts) to a Gaussian. Theoretical photospheric profiles for corresponding stellar parameters were taken into account for equivalent width (EW) measurements.

[1]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

Results

ζ Tau

• Data on the Fe II 5317 & 6383, Si II 6347 & 6371, Na I 5889 & 5995, He I 5876 Å, and Hα lines were analysed (see Fig 1).

• All the lines were found to show regular RV variations with two distinct periods: the binary orbital period (132.9 days) and a longer one (1518.3 days).

• The line emission components vary in anti–phase with respect to the absorption components during the long-term cycle, while their phase curves are the same for the binary orbital cycle (see Fig. 2).

• Longer-term RV variations have been previously observed in the 1960's (period 2466.2 days), no regular variations have been detected in 1980's, the new long-term periodic phase has begun in 1995 (see Fig. 2).

• The V/R ratio of the Hα profile seems to follow the long-term RV variations with a phase shift and a larger scatter around the cosine fit.

• The Hα line central emission peak (Fig. 3) has a larger amplitude ($\sim$ 60 km s^{-1}) of the orbital period variations than that of the absorption lines ($\sim$ 20 km s^{-1}). Its appearance may affect the V/R ratio and make the V/R vs. time dependence less regular than that of RV.

π Aqr

• Analysis of the available photometric data shows that π Aqr brightened between the late 1950's and early 1970's, passed through a maximum brightness phase near 1985, dimmed between 1985 and 1995, and has remained in a low-brightness phase through the present time (see Fig. 4).

• In 1995, after a decade of decreasing emission, the star almost completely lost its line emission. The only line in which small signs of emission are currently seen is Hα. Note that this also corresponds with the onset of a persistent low state in the polarization.

• The Hα emission component was found to display regular RV variations with the period 84.273 days (Fig. 5).

γ Cas

• Comparison of our data with previously published results shows that the RV of the Hα central peak shifted significantly to negative values since the early 1980's (Fig. 6).

• The Hα profile showed very slow variations, mostly in the red wing, in 1997–2000. The V/R ratio was less than 1 in 1993–1998, while the blue peak seems to merge with the central one later on.

• The emission peak RV of the He I 5876 and Fe II 5317 Å lines show a trend towards positive velocities, while the central peak of Hα displays the opposite trend (Fig. 7).

Suggestions and Conclusions

ζ Tau

- A new phase of the long-term RV and V/R variations is detected since 1995.
- All the observed spectral lines also show similar RV variations with the binary orbital period. However, no traces of the secondary component have been found.

π Aqr

- Periodic RV variations of the Hα emission peak during the weak–disk phase are detected for the first time. We suggest that they may be due to the orbital motion of a binary component.

γ Cas

- A new phase of spectroscopic variations is detected since 1993. Its main features are a gradual decrease of the Hα line strength, a gradual shift of the Hα central peak RV towards more negative values, and similar RV shifts of some other observed emission lines (He I 5876 and Fe II 5317 Å) towards more positive values. The merging of the central and blue emission components of Hα is likely a result of their opposite RV shifts.
- The opposite RV shifts might imply different formation regions of the observed emission lines. For instance, the central peak of Hα may be formed around the possible secondary (Haberl 1995), while other emission lines may be formed in the disk around the primary (visible) component.

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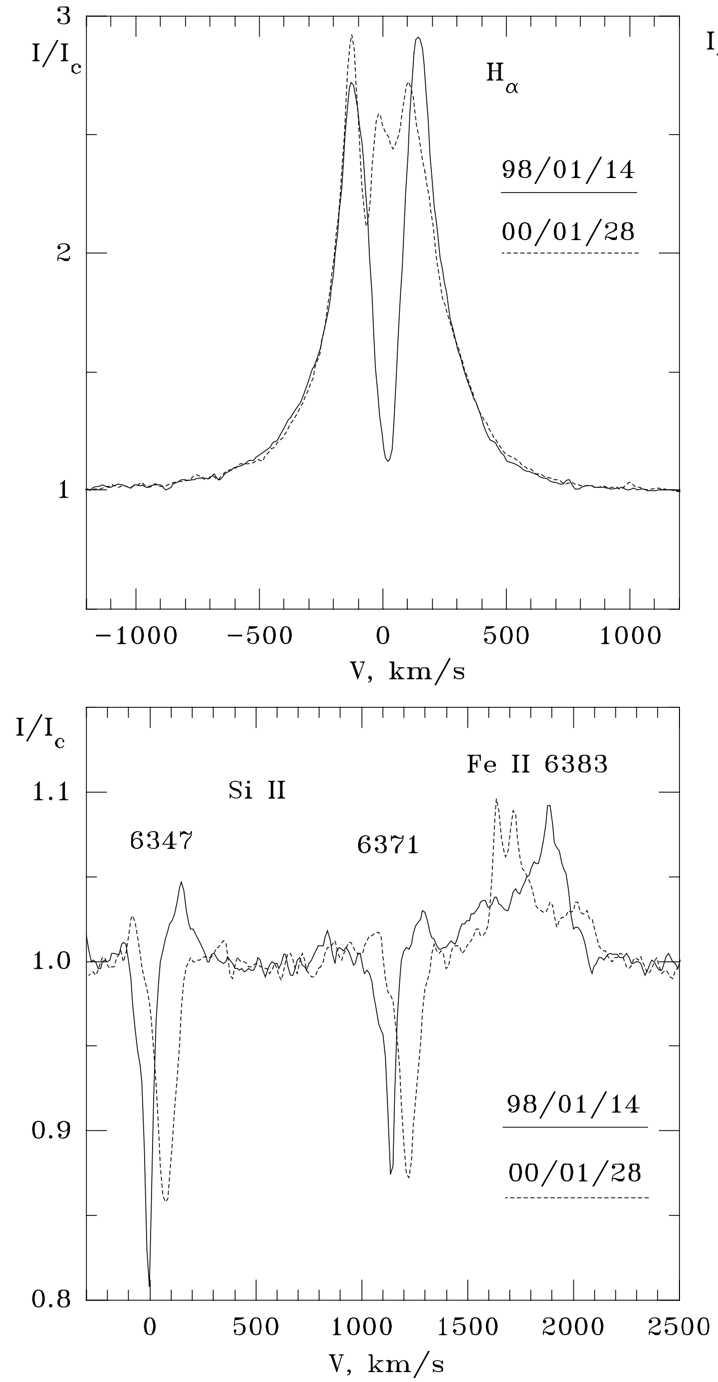

Figure 1: ζ **Tau.** Spectral line variations (Ritter data). Solid lines represent the spectrum obtained on 1998 January 14, while dashed lines show that of 2000 January 28. The intensity is normalized to the underlying continuum, and the heliocentric RV scale is given in $\mathrm{km\,s^{-1}}$.

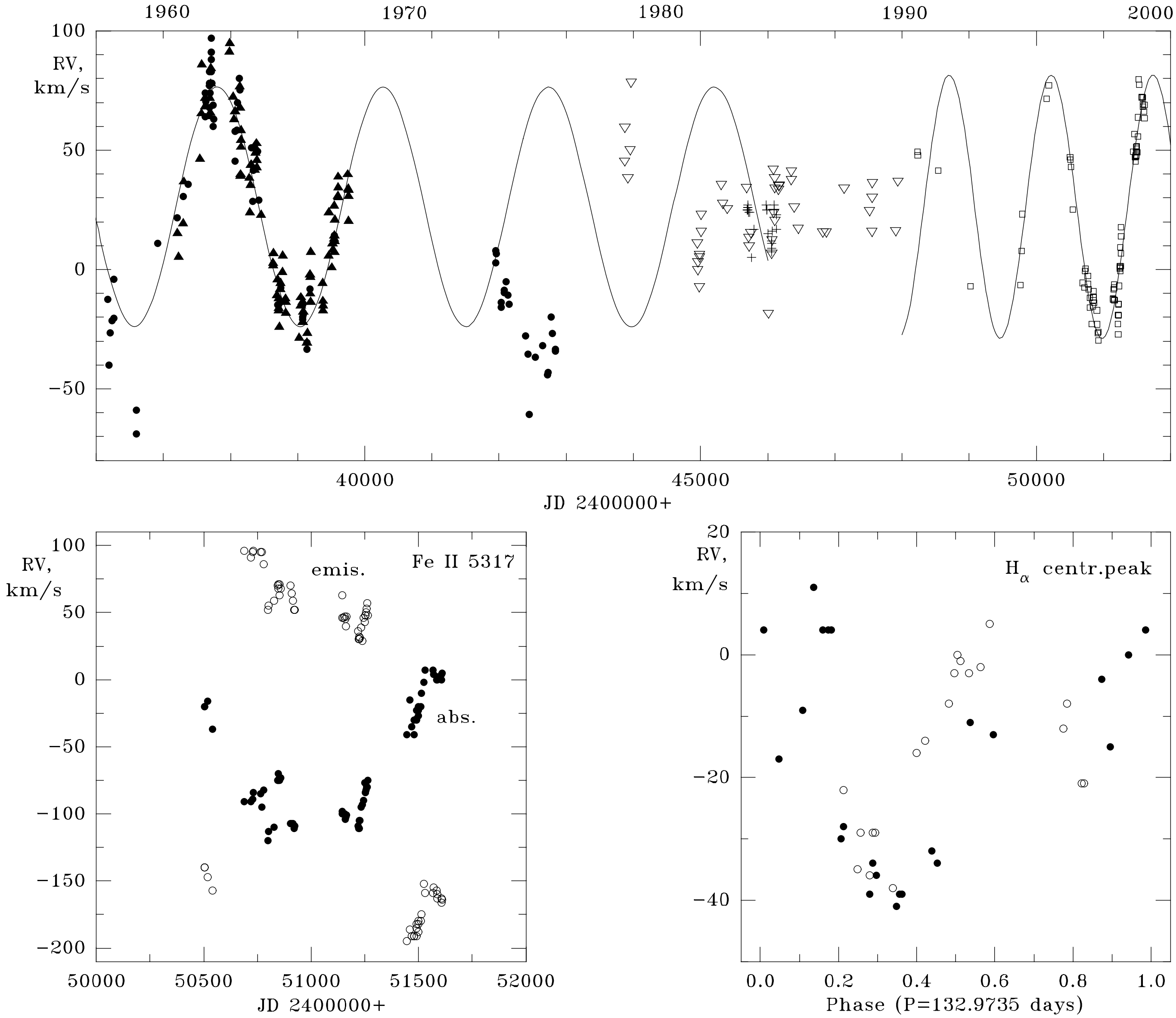

Figure 2: ζ **Tau.** Long–term RV variations. The upper panel shows the RV behavior from 1957 to 2000. Filled circles represent data from Harmanec (1984), filled upward triangles from Delplace (1970), pluses from Jarad et al. (1989), open downward triangles from Guo et al. (1994), and open squares from Ritter. Solid lines show cosine fits to the data with the periods of 2466 (left curve) and 1518 (right curve) days.

Two lower panels show Ritter data. The left panel displays long-term RV variations of the Fe II 5317 Å line. Open circles refer to the emission component, while filled circles refer to the absorption component. The right panel displays RV variations of the Hα central peak. Open circles refer to 1998 data, while filled circles refer to 1999 data.

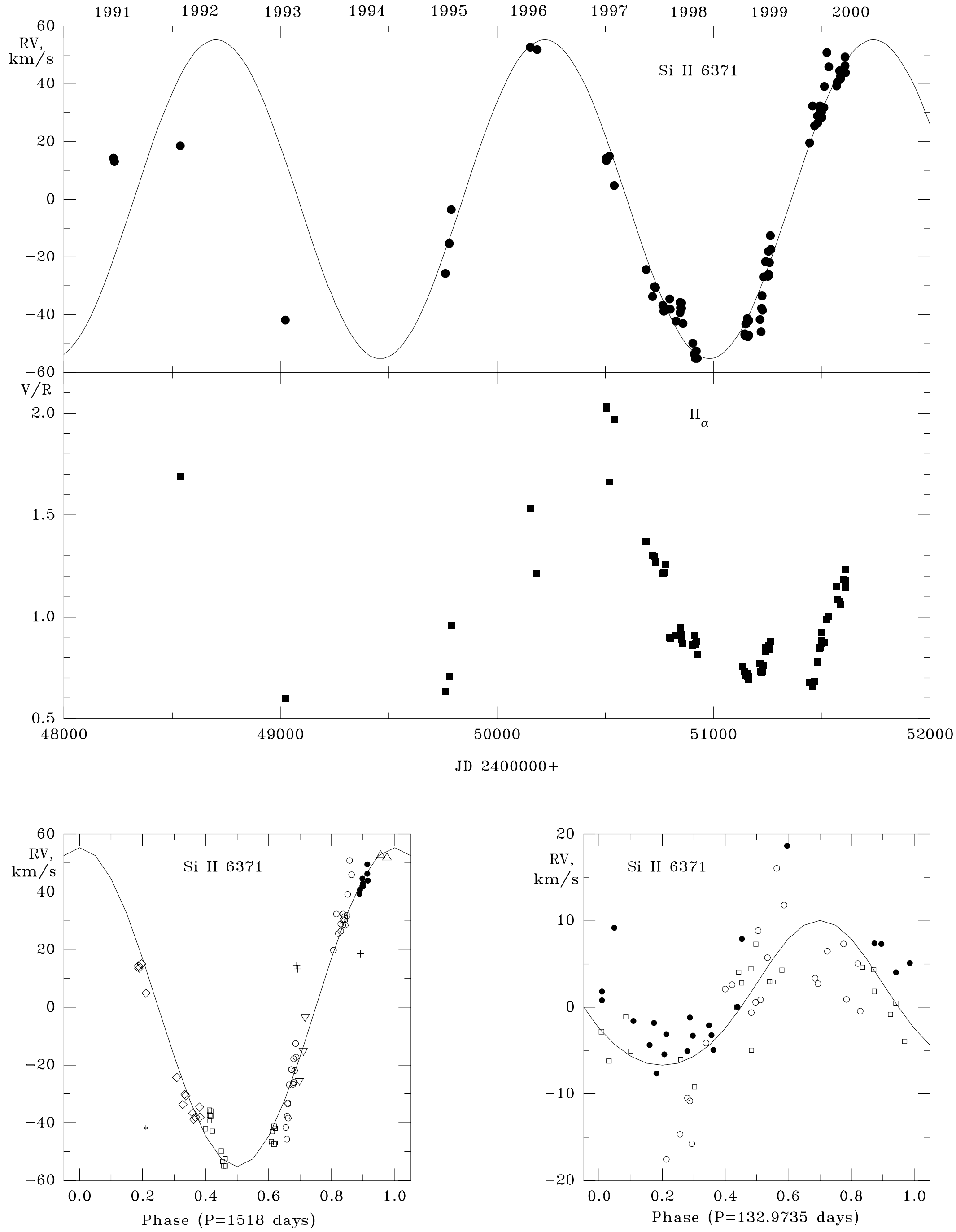

Figure 3: ζ **Tau.** Ritter data. The upper panel shows RV variations of the Si II 6371 Å line absorption component (solid line is the cosine fit to the data with period 1518 days and amplitude 55 $\mathrm{km\,s^{-1}}$) and V/R ratio of the Hα emission peaks. The other panels show the RV variations of the Si II 6371 Å line with the periods 1518 (left) and 132.9735 (right) days. Different symbols on the lower panels denote data of 1990/91 (pluses), 1993 (asterisk), 1995 (downward triangles), 1996 (upward triangles), 1997 (diamonds), 1998 (squares), 1999 (open circles), and 2000 (filled circles).

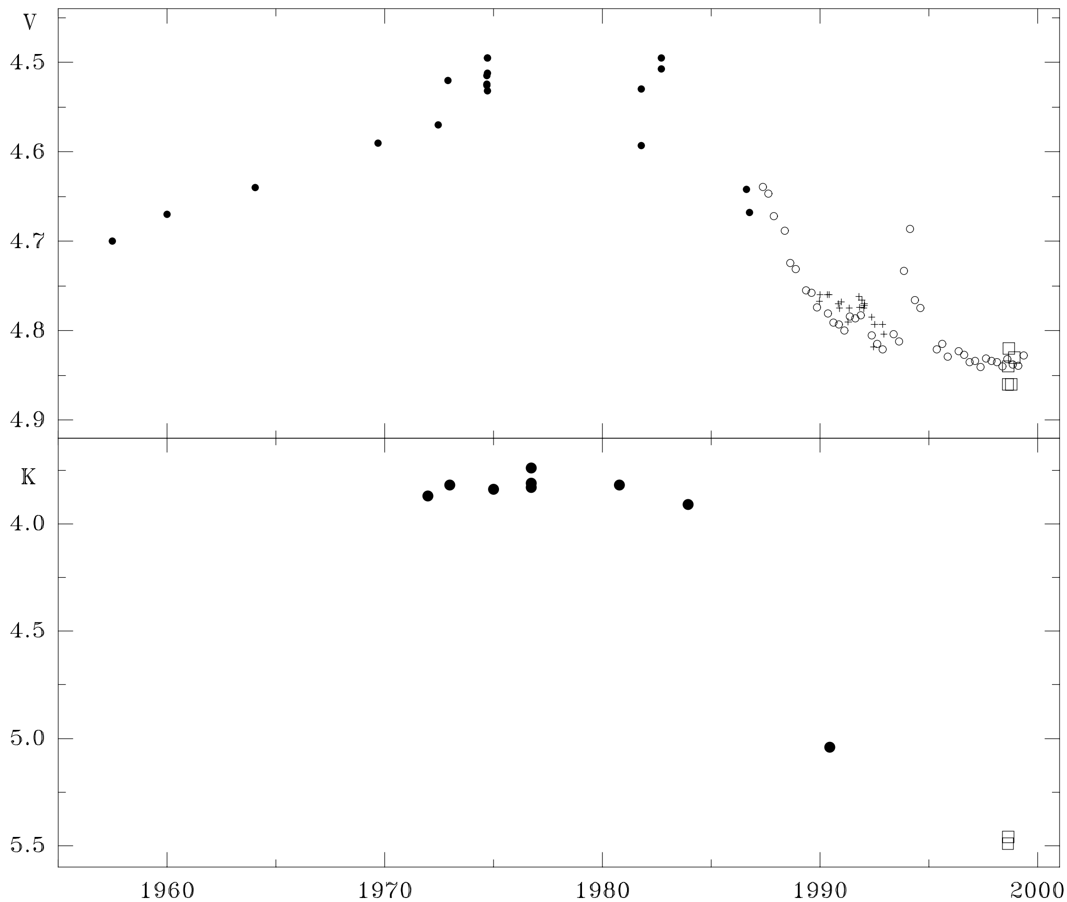

Figure 4: π **Aqr.** The V–band (upper panel) and K–band (lower panel) light curves from 1955 to 2000. Filled circles represent data collected from the literature, pluses show HIPPARCOS data (ESA 1997) translated into the standard photometric system using formulae by Harmanec (1998), open circles and open squares are data from Bjorkman et al. (2000).

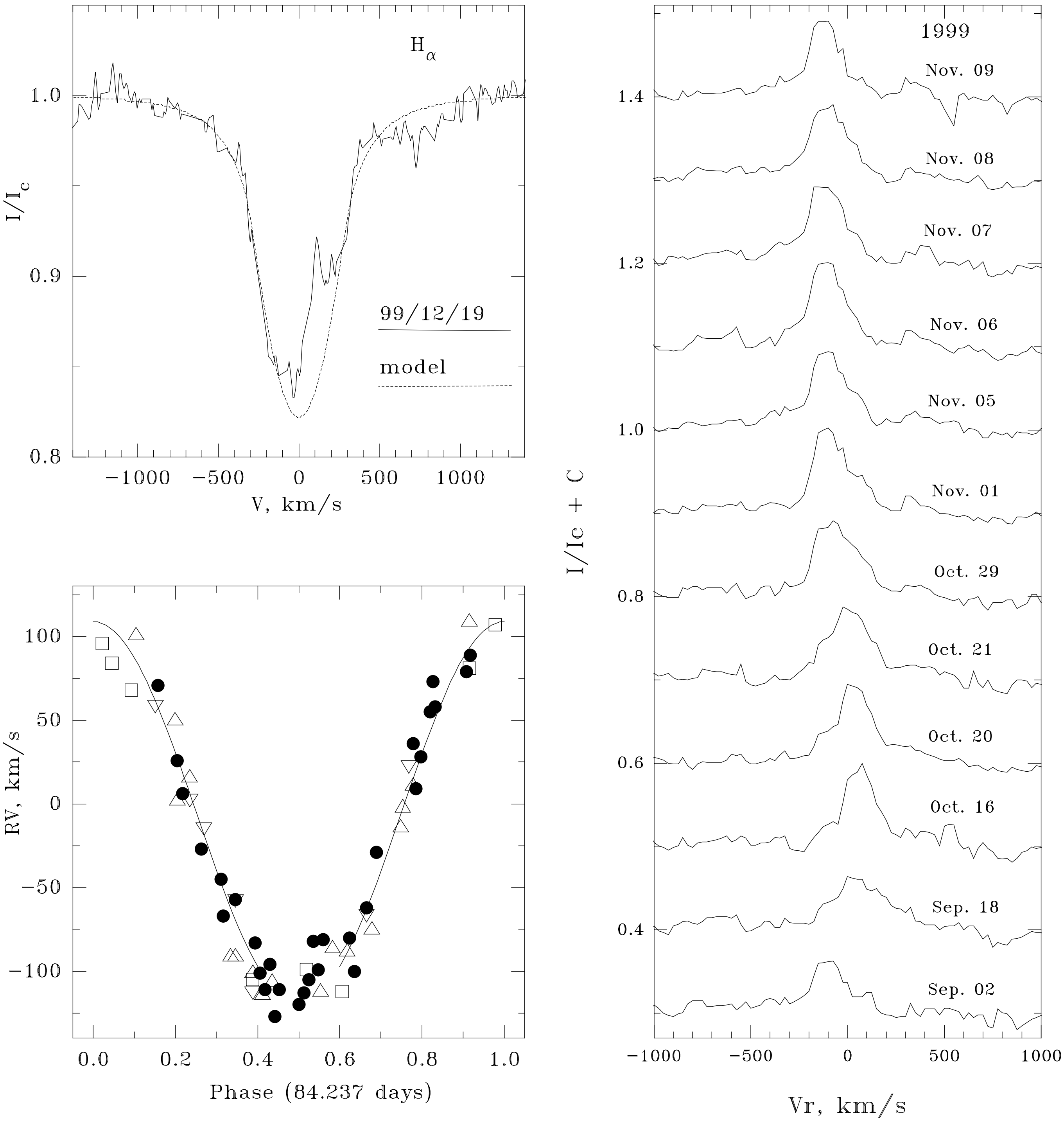

Figure 5: π **Aqr.** RV variations of the Hα profile in 1996–1999 (Ritter data). Upper left panel displays the sample Hα profile obtained on 1999 December 19 (solid line) and the theoretical photospheric profile for $T_{\rm eff}$=25000 K, log g=3.5, v sin i=280 km s^{-1} (Kurucz 1994). Right panel shows individual profiles of the Hα emission peak after the photospheric profile subtraction (data obtained from 1999 September 2 to 1999 November 9). The lower left panel shows the phase curve for the RV of the Hα emission component folded onto the period 84.273 days (open squares represent data of 1996, upward triangles of 1997, downward triangles of 1998, and filled circles of 1999).

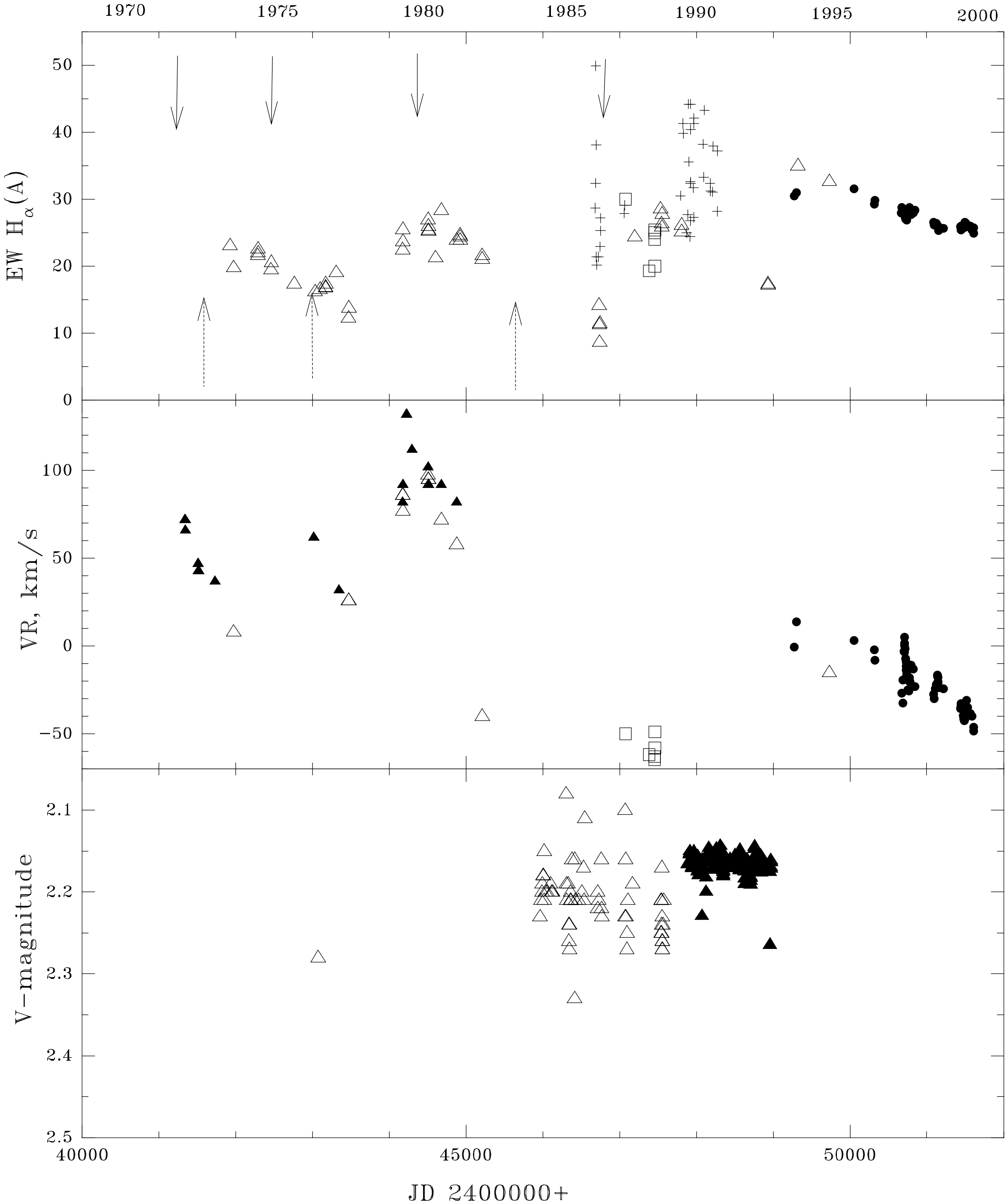

Figure 6: γ **Cas.** Long–term data. Upper panel shows EW variations of Hα, middle panel shows RV variations of the Hα and Hβ central peak, while lower panel shows the V-band light curve. Open triangles represent data collected from the literature, filled triangles are HIPPARCOS data (ESA 1997), open squares are our data obtained in Ukraine, pluses are data obtained at the Krimean Observatory, and filled circles are Ritter data. Downward arrows show positions of the V/R maxima for Hβ, while upward arrows show positions of the R/V minima (data from Doazan et al. 1987).

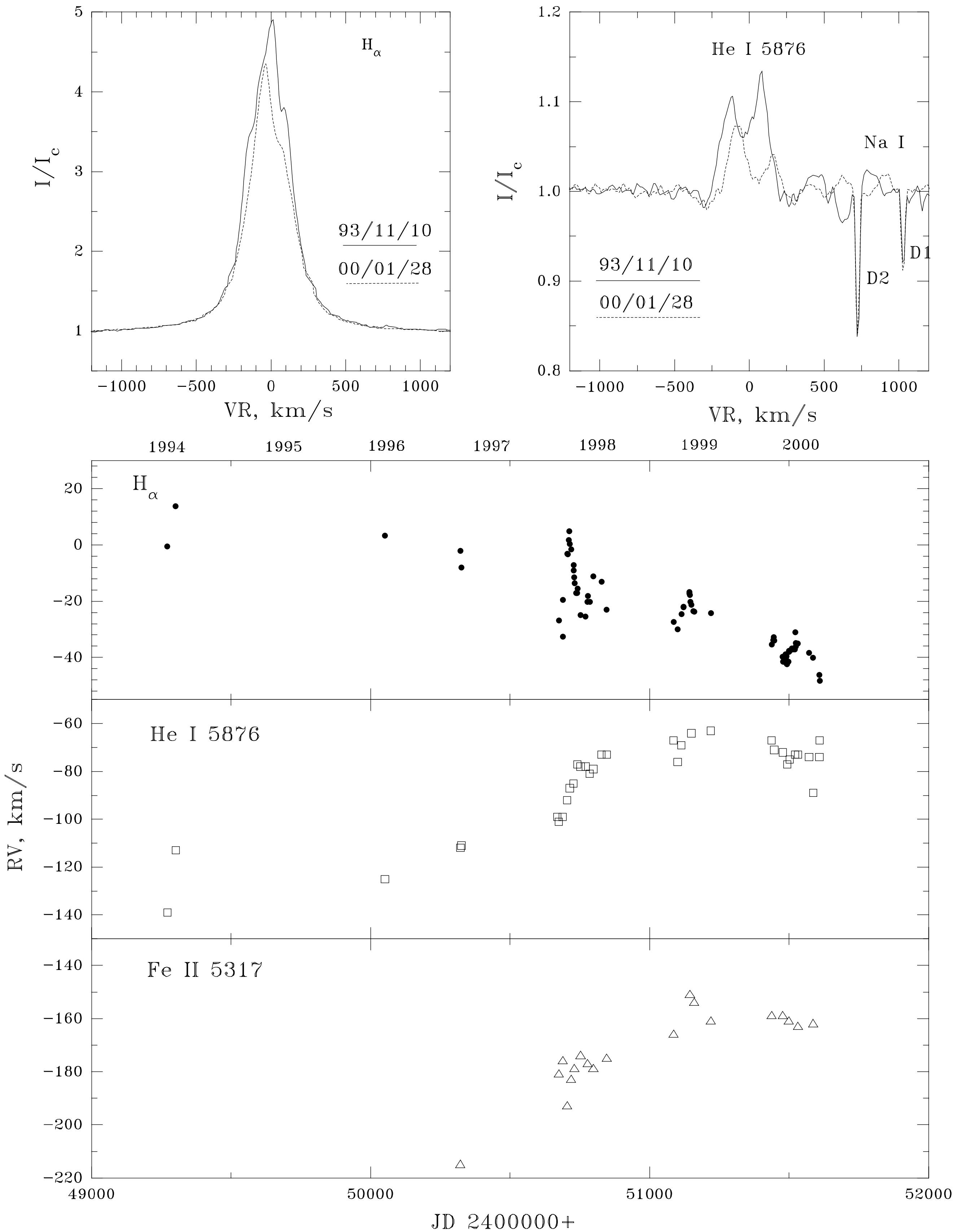

Figure 7: γ **Cas.** Ritter data. Two upper panels show examples of the emission line profile variations. Solid lines represent the data obtained on 1993 November 10, while dashed lines represent data obtained on 2000 January 28. Three lower panels show RV variations of the Hα central peak, red peak of the He I 5876, and the blue peak of the Fe II 5317 Å line, respectively.