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Time-resolved spectroscopy and photometry of the eclipsing polar HU Aquarii(=RXJ2107-05)

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Abstract. We present the results of optical time-resolved spectroscopy and photometry of the eclipsing polar HU Aquarii, obtained with the help of the scanner of the 6 m telescope in July, 1994 and the CCD photometer of the 1 m telescope in September, 2002. The parameters of Balmer and HeII emission lines in the spectra of HU Aqr have demonstrated significant variations with the phase of the orbital period on a time-scale of 5–10 min and from day to day. Spectral light curves (integrated flux in the range of wavelengths 4000–5000Å) have also shown significant variability. The bottom of the primary eclipses in the spectral light curves was 318 ± 12 s with variable ingress (328–388 s) and egress (85–333 s). The form of the spectral light curves is strongly variable on a time-scale of 1–1.5 hours. The radial velocity curves on July 14, 1994 demonstrated deviation from a sinusoid near the orbital phase 0.5, which is considered to be the result of occultation of the magnetic part of the accretion stream by the white dwarf. At the same time, the spectral light curve showed several dips:

– at phase 0, the eclipse of the white dwarf and the accretion stream by the secondary;

– at phase ≈ 0.85, the pre-eclipse dip due to the eclipse of the accretion spot by the accretion stream;

– at phase 0.5, the dip which, as we suppose, is caused by the eclipse of the accretion spot by the white dwarf;

– at phase 0.46, the pre-eclipse dip due to the eclipse of the accretion spot by the magnetic part of the stream.

The two pre-eclipse dips at phases 0.85 and 0.46 indicate that the accretion spot is located in the magnetosphere between two parts of the accretion stream coming from the spot along the field lines in approximately opposite directions. The direction of the field lines and the character of perturbation of the emission lines and the spectral light curve at phase 0.5 are indicative of a hot spot, where the horizontal or ballistic part of the stream is threaded onto the magnetic field lines of the white dwarf. The duration of the dip at phase 0.5 gives the upper limit for the distance of $\approx 12R_{wd}$ from the center of the white dwarf to the accretion spot. The location of the accretion spot is far from the base of the accretion column and should be considered as a second hot spot in the system. The hot spot is the principal source of the optical radiation of the system in the high state of accretion. The absence of the dips at phases 0.5, 0.46 and 0.85 on other neighboring dates of our observations is evidence of instability of the accretion geometry on a time-scale of 1 day.

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Photometric observations during two nights in September 2002 found HU Aqr in the intermediate state, closer to the low state of brightness of the system. The light curve in the V band showed only the primary eclipse without the dips at phases 0.5 and 0.85.

Key words: accretion – stars: individual: HU Aqr (RXJ2107-05) – stars: binaries: general – stars: cataclysmic variables

1 Introduction

Magnetic cataclysmic variables (MCVs) are close binary stars in which a Roche lobe–filling late–type secondary transfers matter to a strongly magnetized white dwarf primary. Polars or AM Her stars form a subclass of MCVs and include synchronous systems in which the spin period of the white dwarf is equal or very close to the orbital period. Accretion on the white dwarf is the principal process in the stars, and study of instability of accretion geometry in eclipsing systems can give important information about location of emission regions inside the systems. According to the standard model of polars (Liebert and Stockman 1985; Cropper 1990; Warner 1995) the accretion stream leaves the secondary via Roche-lobe overflow at the inner Lagrangian point and follows a ballistic trajectory down to the radius where the magnetic pressure overcomes the ram pressure. At this point the stream is threaded onto the magnetic field lines of the white dwarf and accretes onto a small area near one or both magnetic poles.

The threading process is highly non-linear and therefore difficult for theoretical analysis, however, X-ray emission from this interaction region caused by dissipative heating was predicted to occur (Liebert and Stockman 1985), but never observed. Observationally, the question of location of the stream and the brightness distribution along the accretion flow was significantly advanced by mapping experiments of emission line and continuum radiation in two eclipsing polars, HU Aqr and UZ For (Hakala 1995; Harrop-Allin et al. 1999a,b; Heerlein et al. 1999; Kube et al. 2000).

HU Aqr was discovered as a highly modulated soft X-ray source with a period of 125.02 min by the ROSAT Wide Field Camera (RE 2107-05; Hakala et al. 1993) and independently by the X-ray telescope (RXJ 2107.9-0518; Schwope et al. 1993). Multiple follow-up optical and X-ray observations show that the object is the brightest MCV ($V \approx 15.3$) (Shwope et al. 1993; Schwope et al. 2001).

The accretion stream mappinng of HU Aqr predicts a bright spot of hydrogen and helium line emission in the threading region of the stream (Vrielmann & Schwope 2001). A bright spot similar to that on the brightness map was found in the observations of HU Aqr in a low accretion state (Hakala 1995).

Using the technique for indirect imaging of the accretion stream in the polar HU Aqr, it was found that there was no significant brightening in the threading region, and in the low state the stream threads onto the magnetic field closer to the inner Lagrangian point than in the high state (Harrop-Allin et al. 2001).

The application of the eclipse mapping technique to the observations of the polar HU Aqr with the help of the superconducting tunnel junction camera revealed enhanced brightness towards the accretion region from irradiation and enhanced brightness in the threading region because of magnetic heating from the stream–field interaction (Bridge et al. 2002).

A combined analysis of low-resolution spectroscopy and high-speed optical photometry of the polar HU Aqr, obtained in its high accretion state, revealed the existence of an accretion arc with a total extent of about 20°. The soft X-ray accretion spot is located at the far end of the arc, where the bulk of matter is accreted. The arc is likely to be more extended than the foot-line of field lines connecting to the ballistic accretion stream in a dipolar geometry. This, together with the required tilt of the accreting field lines, suggests a more complex magnetic geometry than a simple dipole (Schwope et al. 2003).

The observations of the HU Aqr actually confirmed the prediction of existence of a hot spot in the threading region (Liebert & Stockman 1985), except for X-ray radiation from this region. However, additional observational information about the threading region in MCVs is extremely important. We present here the results of the optical time-resolved spectroscopy and photometry of the eclipsing polar HU Aqr.

2 Observations

Spectral observations were made in the Special Astrophysical Observatory on July 11, 14, 15 and 16, 1994 using the spectrograph SP–124 (Afanasiev et al. 1991) placed at the Nasmyth secondary focus of the 6 m telescope (BTA). The spectrograph equipped with a 1200 lines/mm grating gave a reciprocal dispersion of 50 Å/mm. A multichannel photon-counting system or a television scanner with two lines of 1024 channels recorded two spectra simultaneously (Somova et al. 1982; Drabek et al. 1986). The width of the slit was $2''$. The spectra were obtained in a wavelength passband of $\approx$ 1000 Å within the range 3900–5100 ÅÅ with a dispersion of 1 Å/channel (spectral resolution $\approx$ 2 Å) and a temporal resolution of 32 ms. The spectra were recorded continuously, and a He–Ne–Ar lamp was observed before and after the exposures for the wavelength calibration. To analyze the behaviour of the parameters of emission lines (equivalent width, relative intensity, radial velocities of the peak and centroid), we integrated from the original data the spectra with a temporal resolution of 300 s. The spectral light curves or the integrated flux within the wavelength range 4000–5000 ÅÅ were measured from the spectra with a temporal resolution of 50 s.

Photometric observations were carried out at the 1 meter telescope with a CCD photometer in September 2002 during two nights.

3 Results

The mean relative intensity spectra obtained on July 11, 14 and 15, 1994 are presented in Figure 1. As it is typical for MCVs, the spectra contain the emission lines of hydrogen, HeII 4686 Å , HeI, the blend of lines CIII–NIII 4640–4650 Å. The emission lines have narrow and broad components superimposed on each other. In Figure 2 we show time-resolved spectra which were obtained on July 14, 1994. Time increases from bottom to top. The orbital phase is plotted on the right vertical axis. The spectra are normalized to the continuum. The variations of the profiles of the emission lines near orbital phases 0.0, 0.5 and 0.85 are readily seen. Similar variations at phases 0.5 and 0.85 are absent in the spectra recorded on other dates, and we find useful to compare the behaviour of brightness of the object on different dates. Spectral light curves (integrated flux within the range 4000–5000 ÅÅ) on July 11, 14, 15 and 16, 1994 are presented in Figure 3. The bottom of the primary eclipses in the spectral light curves was 318 ± 12 s with variable ingress (328–388 s) and egress (85–333 s). The form of the spectral light curves is strongly variable on a time scale of 1–1.5 hours.

The spectral light curve on July 14, 1994 (middle panel) shows:

(a) the dip at phase 0.0 associated with the primary eclipse of the white dwarf and the accretion stream by the secondary;

(b) the dip at phase 0.85 or the primary pre-eclipse dip due to the eclipse of the accretion spot by the accretion stream;

(c) the dip at phase 0.5 caused by the secondary eclipse of the accretion spot and accretion stream by the white dwarf;

(d) the dip at phase 0.46 or the secondary pre-eclipse dip due to the eclipse of the accretion spot by the accretion stream.

The features (a, b) are known and have been observed in the X-ray and optical light curves (Schwope et al. 2001), whereas the features (c, d) are new and unstable. The behaviour of the equivalent widths of the $H\beta$ emission line is shown in Figure 4. The maximum of equivalent width at phases 0.25–0.3, observed on July 11 and 14, 1994, corresponds approximately to the direction of the normal to the horisontal part of the accretion stream. Radial velocity curves measured from the peaks of the $H\beta$ line are plotted in Figure 5. It is easy to see the significant deviations from a sinusoid of the curves, which reflect perturbations of the profile of the $H\beta$ line simultaneously with the features (c, d) in the spectral light curves. The detected spectral variations permit one to consider the feature (c) as a result of the eclipse of the accretion spot and the stream by the white dwarf and the feature (d) as the eclipse of the accretion spot by the magnetic part of the accretion stream. In this case the interpretation of the features (c, d) is similar to that of the features (a, b). The duration of the secondary eclipse gives the upper limit for the distance from the center of the white dwarf to the accretion spot of $\approx 12R_{wd}$. The presence of two pre-eclipse dips suggests that the accretion spot is located in the magnetosphere of the white dwarf between two parts of the accretion stream which flow from the spot along the field lines in approximately opposite directions.

The direction of the field lines, the phase of the secondary eclipse and the character of perturbation of the emission lines at phase 0.5 exclude the location of the accretion spot in the accretion column and indicate that the hot spot is in the region where the horizontal or ballistic part of the stream is captured by the magnetic field. Such a hot spot was predicted by Liebert and Stockman (1985). A comparison of the X-ray eclipse of the accretion spot by the white dwarf (Schwope 2001) and the eclipse of the accretion spot in our spectral light curve on July 14 shows that the detected hot spot is far from the spot at the base of accretion column and should be considered as a second hot spot expected in the threading region of the accretion stream. This spot is the principal source of the optical radiation of the system in the high state of accretion. The absence of similar events on other neighboring dates of our observations is evidence of instability of the accretion geometry on a time-scale of 1 day.

Photometric observations during two nights in September 2002 found the system HU Aqr to be in an intermediate state, closer to the low state of its brightness. The light curve in the V band, showing only the primary eclipse without the dips at phases 0.5 and 0.85, is presented in Figure 5.

4 Conclusions

We have presented the results of optical time-resolved spectroscopy and photometry of the eclipsing polar HU Aquarii. We have found that the parameters of the Balmer and HeII emission lines in the spectra of HU Aqr reveal significant variations over the orbital period and on a time-scale of 1 day. On July 14, 1994 we recorded variability of the spectral light curve occurring simultaneously with the perturbations of the emission line profiles caused by

- the eclipse of the accretion spot by the part of the accretion stream, which showed up as the secondary pre-eclipse dip at phase 0.46;
- the eclipse of the accretion spot and the part of the accretion stream close to the white dwarf by the white dwarf, presented as the dip at phase 0.5.

The phase and duration of the secondary eclipse and the character of perturbation of the emission lines at phase 0.5 indicate that the hot spot is in the magnetosphere where the ballistic part of the stream is captured by the magnetic field (Liebert and Stockman 1985). Photometric observations during two nights in September 2002 found HU Aqr in an intermediate state, closer to the low state of brightness of the system. The light curve in the V band showed only the primary eclipse without the dips at phases 0.5 and 0.85.

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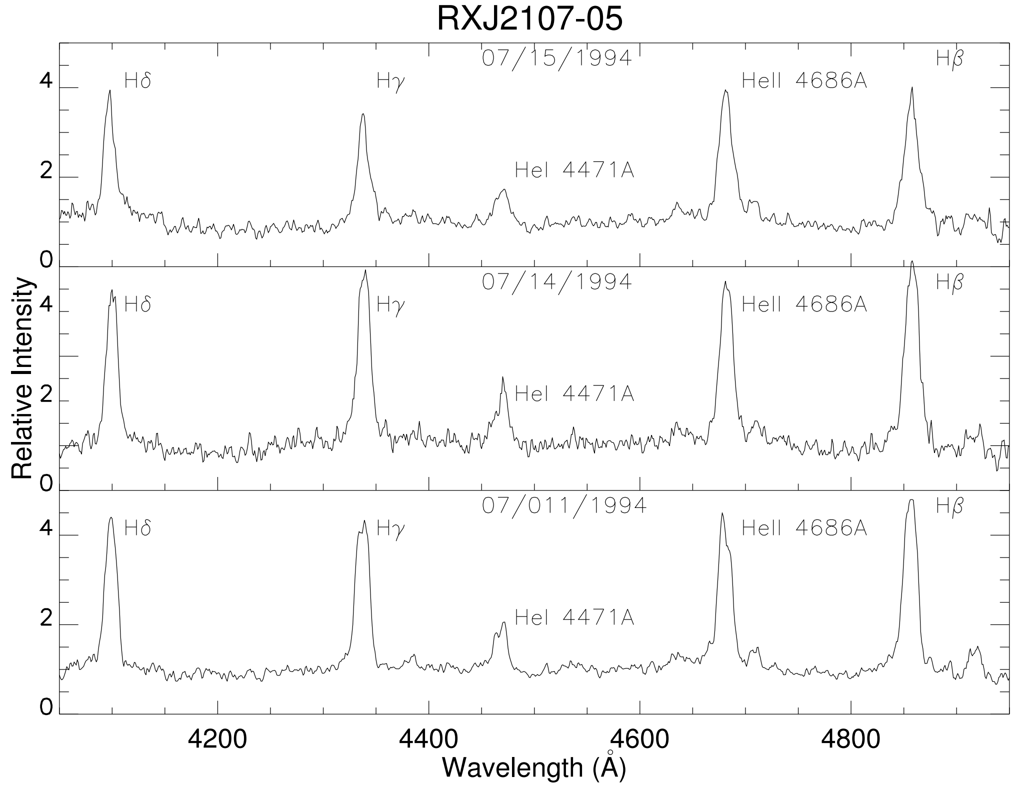

Figure 1: *The mean relative intensity spectra which were obtained on July 11, 14 and 15, 1994.*

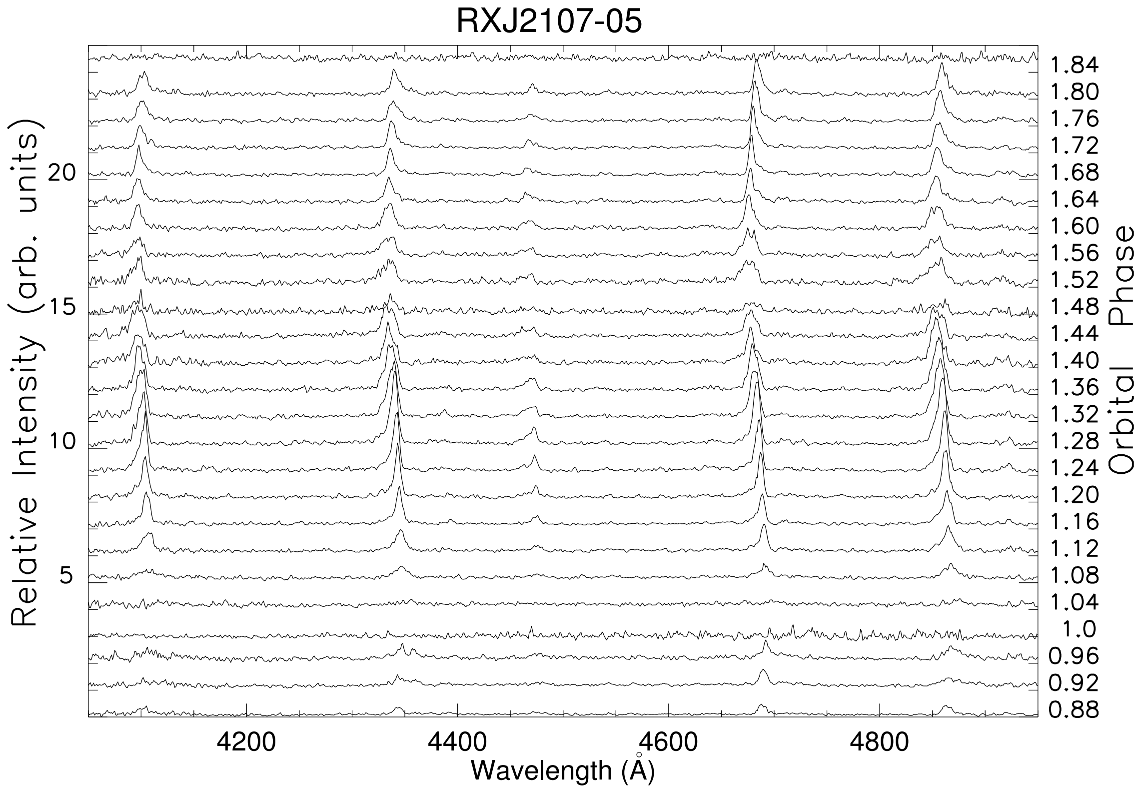

Figure 2: *Variations of the spectra which recorded on 07/14/1994 over orbital phase.*

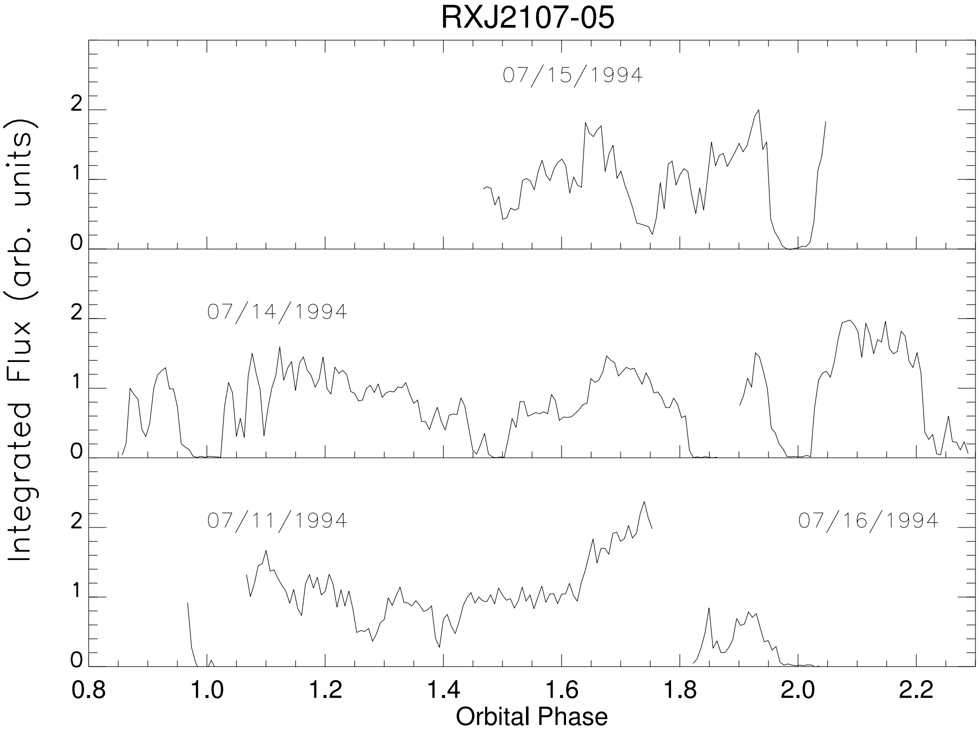

Figure 3: *The spectral light curves obtained on July 11, 14, 15, 1994.*

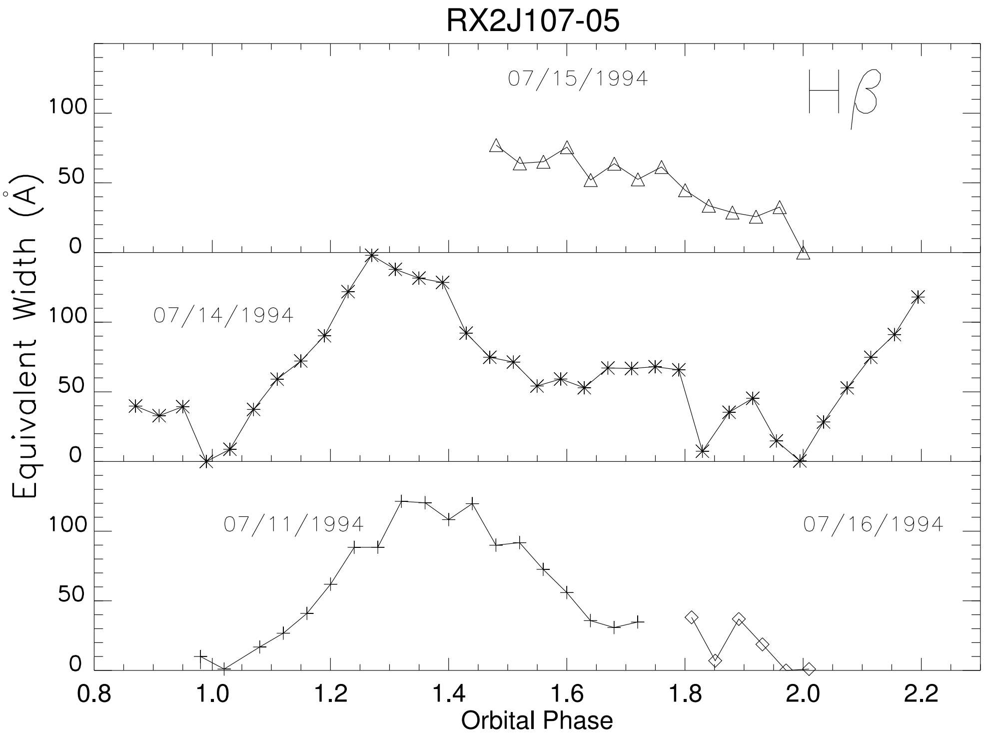

Figure 4: *The variations of the equivalent widths of the Hβ emission line over the orbital period on July 11, 14, 15, 16, 1994.*

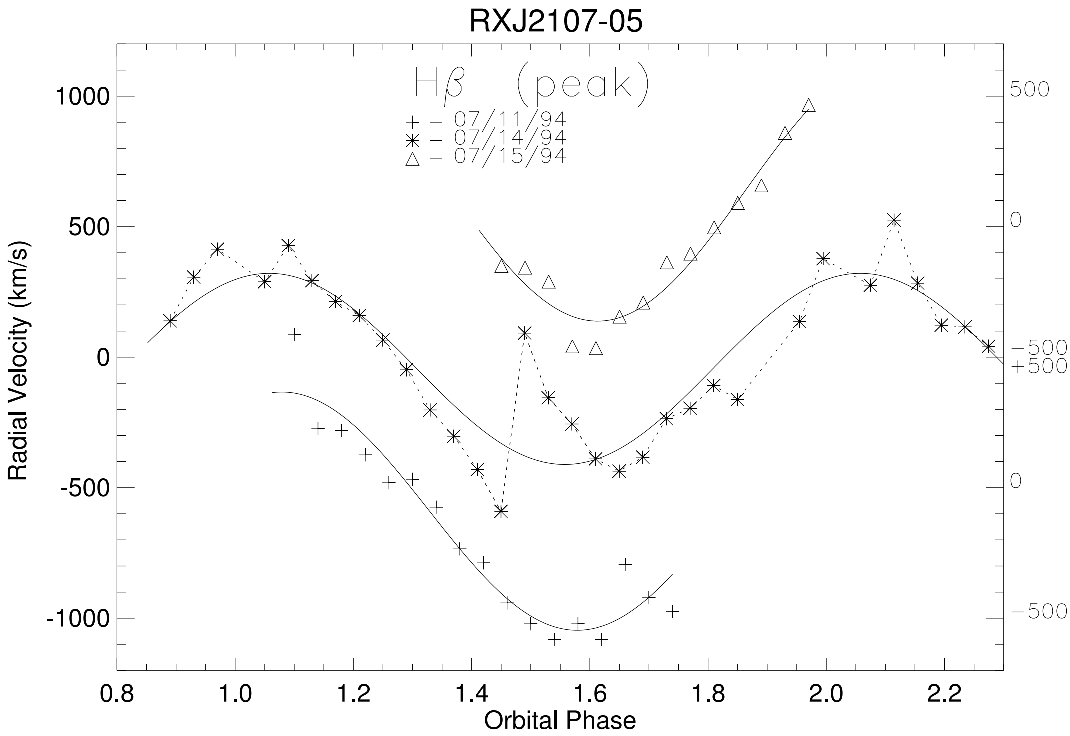

Figure 5: *The radial velocity curves measured from the peaks of the Hβ emission line for the observations on July 11, 14, 15, 1994.*

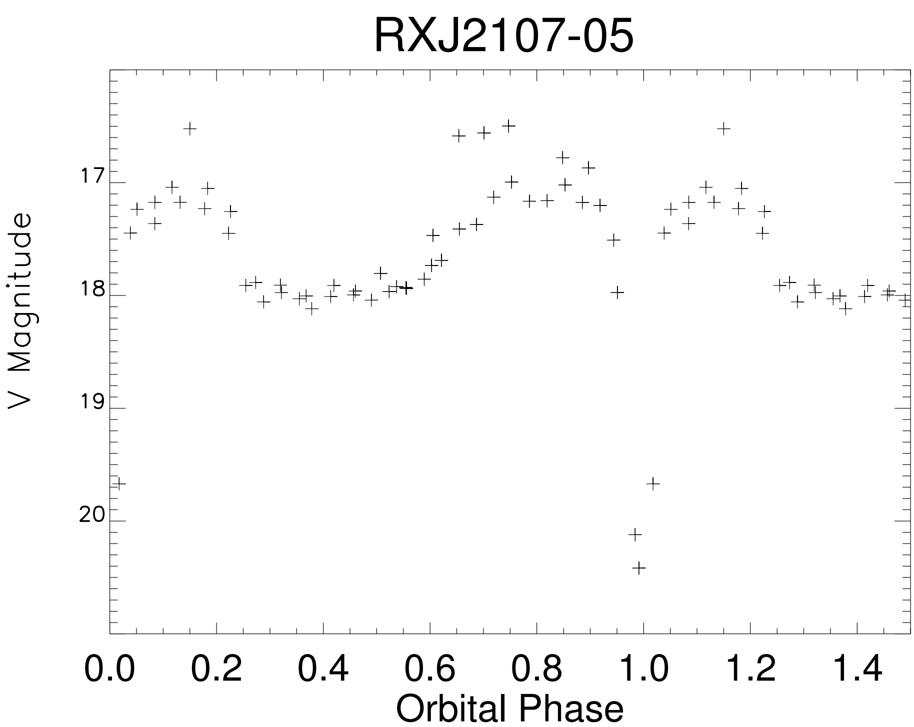

Figure 6: *The light curve in V band obtained in September 2002.*