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U Geminorum: a Test Case for Orbital Parameters Determination

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Abstract. High-resolution spectroscopy of U Gem was obtained during quiescence. We did not find a hot spot or gas stream around the outer boundaries of the accretion disk. Instead, we detected a strong narrow emission near the location of the secondary star. We measured the radial velocity curve from the wings of the double-peaked Hα emission line, and obtained a semi-amplitude value in excellent agreement with the ultraviolet results by Long & Gilliland (1999). We present also a new method to obtain K_2, which enhances the detection of absorption or emission features arising in the late-type companion. Our results are compared with published values derived from the near-infrared NaI line doublet. From a comparison of the TiO band with those of late type M stars, we find that a best fit is obtained for a M6 V star, contributing 5% of the total light at that spectral region. Assuming that the radial velocity semi-amplitudes reflect accurately the motion of the binary components, then from our results: $K_{\rm em} = 108 \pm 2$ km s^{-1}; $K_{\rm abs} = 310 \pm 5$ km s^{-1}, and using the inclination angle by Zhang & Robinson (1987); $i = 69\overset{\circ}{.}7 \pm 0.7$, the system parameters become: $M_{\rm WD} = 1.20 \pm 0.05\, M_{\odot}$; $M_{\rm RD} = 0.42 \pm 0.04\, M_{\odot}$; and $a = 1.55 \pm 0.02\, R_{\odot}$. Based on the separation of the double emission peaks, we calculate an outer disk radius of $R_{\rm out}/a \sim 0.63$, close to the distance of the inner Lagrangian point $L_1/a \sim 0.63$. Therefore we suggest that, at the time of observations, the accretion disk was filling the Roche-Lobe of the primary, and that the matter leaving the L_1 point was colliding with the disc directly, producing the hot spot at this location. Specific details not included in the printed version can be found in the Electronic Poster (EP).

Keywords. binaries: close – stars: nova, cataclysmic variable – stars: individual (U Geminorum)

1. Observations

U Geminorum was observed in 1999 January 15 with the Echelle spectrograph at the f/7.5 Cassegrain focus of the 2.1-m telescope of the Observatorio Astrónomico Nacional at San Pedro Mártir, B.C., México. The Thompson 1024×1024 CCD was used to cover a spectral range from λ5200 to λ9100 Å with a spectral resolution of R=18,000. An echellette grating of 150 l/mm, with Blaze around 7000 Å was used. The spectra shows a strong Hα emission line. No absorption features were detected from the secondary star. A complete orbital cycle was obtained with twenty-one spectra with an exposure time of 600s each. Thirteen further spectra were then acquired with an exposure of 300s each. The flux standard HD 17520 and the late spectral M star HR 3950 were observed on the same night.

2. Radial Velocities

We derive radial velocities of the primary star from the prominent Hα emission line by using a method based on a cross-correlating technique and also using the standard method of measuring the wings of the line. In the case of the secondary star, we were unable to detect any single absorption line in the individual spectra, and therefore it was not possible to use any standard method. However, we propose and use a new method

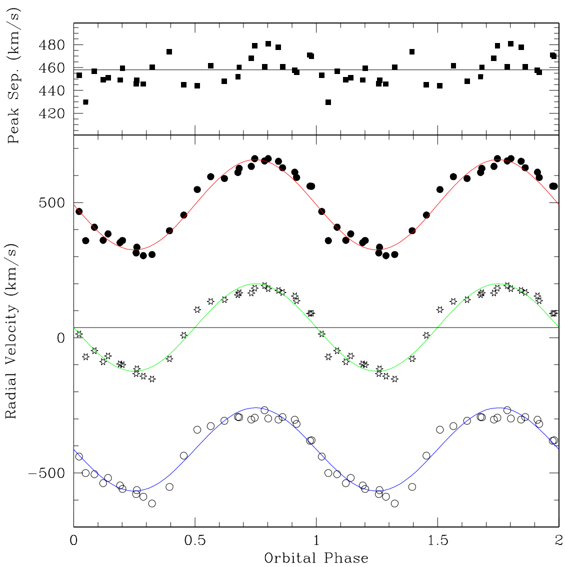

Figure 1. Radial velocity curve of the double peaks. The separation of the peaks has a mean value of about 460 km s^{-1}.

to derive the semi-amplitude of the companion star, based on a co-adding technique (see EP for full details).

2.1. *The Primary Star*

In this section we compare three methods for determining the radial velocity of the primary star, based on measurements of the Hα emission line. We adopt the ephemeris: HJD $= 2,437,638.82566(4) + 0.1769061911(28)\,\mathrm{E}$, for the inferior conjunction of the secondary star. These ephemeris are used throughout this paper for all our phase folded diagrams and Doppler Tomography. Full details can be found in Echevarría, de la Fuente & Costero (2007). To match the signal-to-noise ratio of the first twenty-one spectra, we have co-added (in pairs) the last thirteen exposures. The last three spectra were added to form two different spectra. This is to avoid losing the last single spectrum. This adds to a total of twenty-eight 600 s spectra. A handicap to this approach is that due to the large read-out time of the Thompson CCD we are effectively smearing the phase coverage of these last co-added spectra to nearly 900 s. However, the mean heliocentric time was corrected for each sum.

We have measured the position of the peaks using a double–Gaussian fit. The results are shown in Figure 1. The mean semi-amplitude and peak separation are $K_{\mathrm{em}} = 168 \pm 8$ km s^{-1} and 460 km s^{-1} respectively.

We have cross-correlated the Hα spectra with a specially constructed template. We selected a spectrum close to orbital phase 0.75, a phase at which we should expect a minimum distortion in the peaks due to asymmetric components. The selected spectrum was highly smoothed to minimize high-frequency correlations. This template is shown in the EP. The semi-amplitude of the radial velocity curve is $K_{\mathrm{em}} = 129 \pm 6$ km s^{-1}. The radial velocity curve is shown in the EP.

The Hα emission lines were measured using the standard double–Gaussian technique and its diagnostic diagrams as described in Shafter, Szkody & Thorstensen (1986). For full details see Echevarría, de la Fuente & Costero (2007) and the EP. The semi-amplitude of the radial velocity curve is $K_{\mathrm{em}} = 108 \pm 2$ km s^{-1}. The radial velocity curve is shown in the EP.

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2.2. *The Secondary Star: a new method to determine K_2*

We were unable to detect any absorption features from the secondary star in any single spectra either visually or using the standard cross-correlation technique. We have been able, however, to detect the NaI $\lambda\lambda$ 8183.3, 8194.8 Å doublet and the TiO Head band around λ 7050 Å with a new technique, as well as $H\alpha$ emission as well, which enables us to derive the semi-amplitude K_{abs} of the secondary. The method is fully explained in Echevarría, de la Fuente & Costero (2007) and the EP.

We have applied our criteria to U Gem. The time of the inferior conjunction of the secondary and the orbital period were taken from section 2.1. The results are shown in the EP Figures.

For the NaI doublet $\lambda\lambda$ 8183, 8195 Å, the spectra were *co-phased*, varying K_{pr} between 250 and 450 $km\,s^{-1}$. The line depth of the blue and red components of the doublet (stars and open circles respectively), as well as the mean value of both lines (dots) are shown in the diagram. In both lines we find a best solution for $K_2 = 310\,km\,s^{-1}$. As it approaches its maximum value, the line depth oscillates slightly but in the same way for both lines. We found a similar behavior on the artificial spectra process described above for low signal-to-noise features. The figure (see EP) shows the *co-phased* spectrum of the NaI doublet for our best solution of K_2. Similar results were found for the TiO band and the $H\alpha$ emission with the best solution for $K_2 = 310\,km\,s^{-1}$.

3. Doppler Tomography

Doppler Tomography is a useful and powerful tool to study the material orbiting the white dwarf, including the gas stream coming from the secondary star as well as emission regions arising from the companion itself. A detailed formulation of this technique can be found in Marsh & Horne (1988). The Doppler Tomography results derived here from the Hα emission line were constructed using the code developed by Spruit (1998).

Since our observations of the object cover 1.5 orbital cycles, and with the intention to avoid disparities on the intensity of the trailed and reconstructed spectra and on the tomographic map, we have carefully selected spectra covering a full cycle only. In addition to this, we excluded from the calculations of the Tomography map, the spectra taken during the partial eclipse of the accretion disc (phases between 0.95 and 0.05). The results are shown in the EP figure. Here, we present a blow-up of the $H\alpha$ emission near the secondary.

4. Basic system parameters

Assuming that the radial velocity semi-amplitudes reflect accurately the motion of the binary components, then from our results: $K_{em} = 108 \pm 2\,km\,s^{-1}$; $K_{abs} = 310 \pm 5\,km\,s^{-1}$, and adopting $P = 0.1769061911$ and using the inclination angle by Zhang & Robinson (1987); $i = 69.^{\circ}7$ ±0.7, the system parameters become: $M_{WD} = 1.20 \pm 0.05\,M_{\odot}$; $M_{RD} = 0.42 \pm 0.04\,M_{\odot}$; and $a = 1.55 \pm 0.02\,R_{\odot}$.

4.1. *The inner and outer size of the disc*

The dimensions of the disc –the inner and outer radius- can be derived from the observed Balmer emission line. Its peak-to-peak velocity separation is related to its outer radius, while the wings of the line, coming from the high velocity regions of the disc, can give an estimate of the inner radius (e.g., Smak 2001). The peak-to-peak velocity separation, as well as the velocity of the blue and red wings of $H\alpha$ (10% above the continuum), of the 28 individual spectra were measured. From these measurements we derive a mean value of $V_{peak} = 460\ km\,s^{-1}$ and $V_{wings} = 1200\ km\,s^{-1}$.

These velocities are related to the disc radii, which can be obtained from numerical disc simulations, tidal limitations and analytical approximations (see Warner 1995 and

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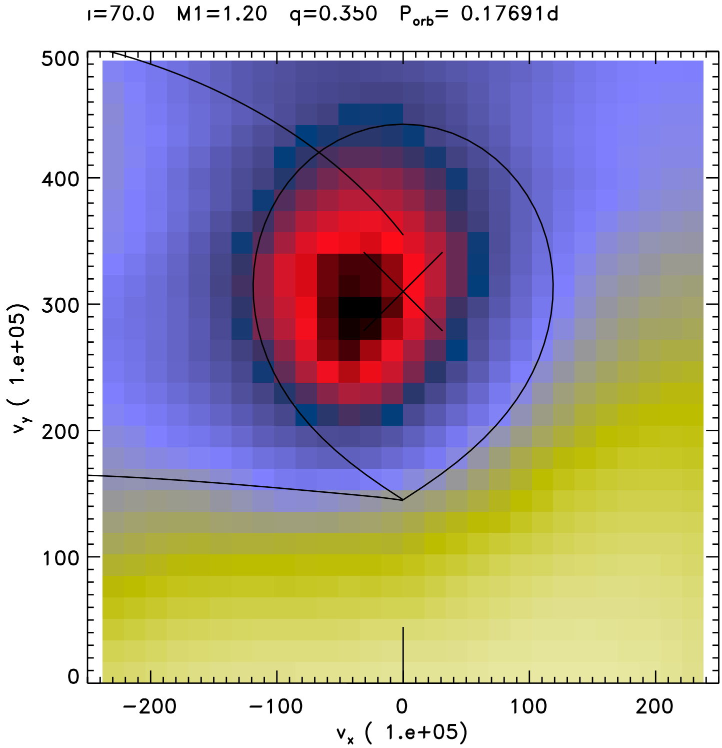

references therein). Here we assume that the material in the disc at radius r is moving with Keplerian rotational velocity V. Then the radius, in units of the binary separation is given by: $r/a = (K_{\rm em} + K_{\rm abs})K_{\rm abs}/V^2$, (e.g., Horne, Wade, & Szkody 1986).

Smak (1981) has shown that the observed maximum intensity of the double-peak emission in Keplerian discs occurs close to the velocity of its outer radius. From the observed value we obtain an outer radius of $R_{\rm out}/a = 0.61$. An inner radius $R_{\rm in}/a = 0.09$ is derived from the wing measurements and the assumption of the Keplerian approximation. These outer radii can be compared with the inner Lagrangian point and the mean R of the primary. The inner radius can be compared with the radius of a white dwarf and with the expected boundary layer radius. The distance R_{L_1}/a from the center of the primary to the inner Lagrangian point is: $R_{L_1}/a = 1 - w + 1/3w^2 + 1/9W^3$, where $w^3 = q/(3(1+q)$ (see Kopal 1959). Using $q = 0.35$ we obtain $R_{L_1}/a = 0.63$. The disc, therefore, appears to be large, almost filling the Roche lobe of the primary, with the matter leaving the L_1 point colliding with the disc directly, producing the hot spot at this location. Full details can be found in the Electronic Poster (EP) and in Echevarría, de la Fuente & Costero (2007).

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