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DOPPLER TOMOGRAPHY OF CATACLYSMIC VARIABLES WITH A 6.5-M CLASS TELESCOPE

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RESUMEN

Se está llevando a cabo un proyecto a largo plazo de espectroscopía de alta dispersión (R ∼ 20000) para observar y analizar una muestra de variables cataclísmicas con el telescopio de 2.1-m en el Observatorio Astronómico Nacional en San Pedro Mártir y el espectrógrafo echelle. La herramienta principal para este análisis es la tomografía Doppler. En esta contribución presentamos nuestro trabajo y abordamos la pregunta: ¿Cómo podríamos mejorar este proyecto con un telescopio de clase 6.5-m?

ABSTRACT

We are conducting a long-term project of high dispersion spectroscopy (R ∼ 20000) to observe and analyze a sample of cataclysmic variables with the 2.1-m telescope at San Pedro Mártir and the echelle spectrograph. The main tool for this analysis is Doppler tomography. In this contribution we summarize our work and pose the question: how can we improve this project with a 6.5-m class telescope?

Key Words: **NOVAE: CATACLYSMIC VARIABLES — TECHNIQUES: MISCELLANEOUS — TECHNIQUES: SPECTROSCOPIC — TELESCOPES**

1. INTRODUCTION

Doppler tomography of cataclysmic variables is a powerful tool in our understanding of the physical properties of accretion disks (Marsh & Horne 1988). For this reason we have undertaken a long-term project to observe a large sample of objects with the echelle spectrograph at the 2.1-m telescope at the Observatorio Astronómico Nacional at San Pedro Mártir. Because these objects are visually faint and most of them require several hours to complete at least one orbital period, there are no high-dispersion spectroscopic observations on large telescopes. In a first paper (Echevarría et al. 2003), the problem of achieving higher velocity-bins in the accretion maps with large telescopes was discussed. In this second contribution we explore this problem further by using our existing observations of U Geminorum to predict the optimal phase resolution and signal-to-noise ratio that we could obtain in larger telescopes.

2. OBSERVATIONS OF U GEMINORUM

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 Thomson 1024×1024 CCD was used to cover a spectral range from $\lambda5200$ to $\lambda9100$ Å with a spectral resolution of R=18,000. An echellette grating of 150 l/mm, with Blaze around 7000 Å was used. The spectrum shows a strong Hα emission line. No absorption features were detected from the secondary star. A first complete orbital cycle was obtained with twenty-one spectra with an exposure time of 600 s each. Thirteen further spectra were subsequently acquired with an exposure of 300 s each. These cover an additional half orbital period. The data reduction was carried out with the IRAF package[2].

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. It uses the emission line profiles observed as a function of the orbital phase to reconstruct a two-dimensional velocity map of the emitting material. A detailed formulation of this technique can be found in Marsh & Horne (1988). The Doppler tomography, derived here from the Hα emission line, was constructed using the code developed by Spruit (1998). A careful interpretation of these

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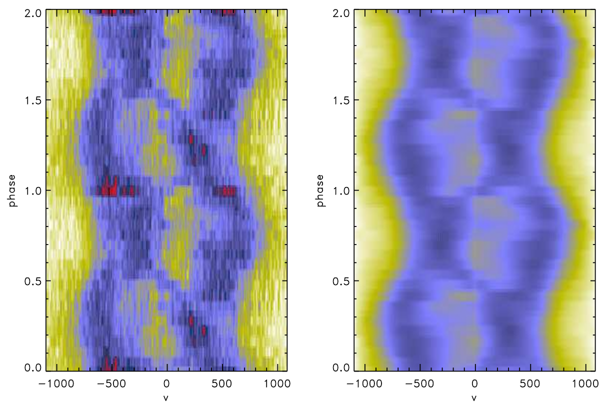

Fig. 1. Trailed spectra of the Hα emission line. Original (left) and reconstructed data (right).

velocity maps has to be made, as the main assumption of the tomography is that all the observed material is in the orbital plane and is visible at all times.

Since our observations of the object cover 1.5 orbital cycles, and with the intention to avoid disparities of the intensity of the trailed and reconstructed spectra and of the tomographic map, we have carefully selected spectra covering a full cycle only. For this purpose we discarded the first three spectra (which have the largest airmass) and used only 18 spectra of the first 21 600 s exposures, starting with the spectrum at orbital phase 0.88 and ending with the one at phase 0.86.

In addition to this, we excluded from the calculations of the tomography map, the spectra taken during the partial eclipse of the accretion disk (phases between 0.95 and 0.05). The original and reconstructed trailed spectra are shown in Figure 1. The data are plotted over twice the orbital period for clarity. In these calculations we have reduced the spectral resolution by a factor of 2.5 due to our limit of 2 GB of random access memory in calculating the Doppler map. This degradation in the spectral resolution does not affect the quality of the maps as we have large phase bins in our data. This will be the topic of Section 4.

The images show the sinusoidal variations of the double profile, which are due to the orbital motion of the disk (and presumably of the white dwarf) around the companion star. However, the typical S-Wave, although clearly visible, is closely associated with the inner Lagrange Point L_1 as can be seen in the Tomographic velocity map shown in Figure 2. A large and very symmetric disk is seen in this Doppler tomography, but the hot spot is located in the vicinity of the L_1 point and the secondary star. Figure 3

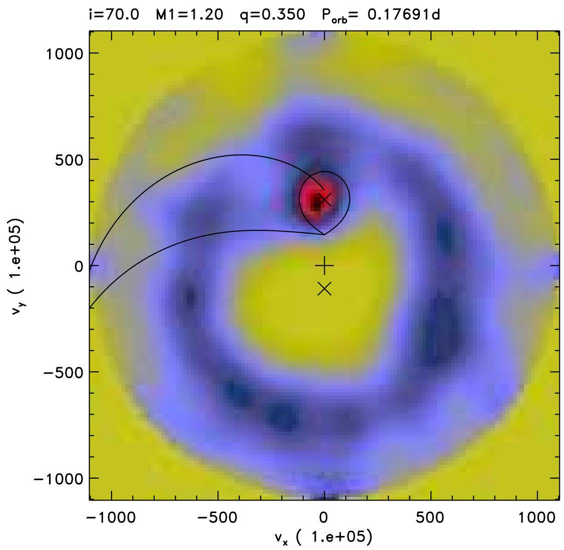

Fig. 2. Doppler tomography.

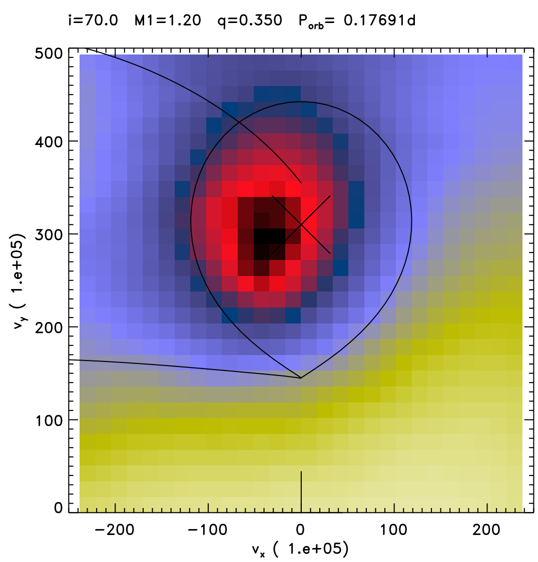

Fig. 3. Hot spot.

shows a blow-up of this region. One must be careful in interpreting this map. Since we are not looking at a spatial map, but rather a velocity map, it is by no means obvious where this Balmer emission line region located. There are two possibilities: either the emission is produced at the surface of the secondary star or in the outer regions of the disk. The v_x velocity of the emission is very close to that of the velocity of the center of mass of the secondary. Since the star is tidally-locked, all points on its surface will have the same velocity as for a rigid body. Therefore it is perfectly possible that the emission would be located in a back-warmed or back-heated inner face. However, if this were the case, the v_y velocity would indicate that the emission is leaning towards the leading hemisphere of the late-type star.

The location of such a compact source is not compatible with the back-illuminated scenario. We would expect a broader and more diffuse emission produced by the re-heating effect from the light emitted in the inner regions of the disk, e.g., the boundary layer. If the hot spot is coming from outside the secondary, i.e., in the outer parts of the disk then the v_x velocity is also consistent with compact emission produced just outside the L_1 point, since the material will still have the velocity of the secondary star. Moreover, if the edge of the disk is close to the inner Lagrange point, then the emission will rapidly obtain a Keplerian velocity and will move along the upper solid line shown in Figures 2 and 3. Otherwise, if the stream does not encounter any material, its path will have a ballistic trajectory as indicated by the lower solid line.

The implications of these results and a detailed analysis of the radial velocity curve of the emission components in U Geminorum will be published elsewhere (Echevarría, de la Fuente, & Costero 2007). Here, we will move on to the topic of using our existing observations of U Geminorum, to predict the optimal phase resolution and signal-to-noise ratio that we could obtain with larger telescopes to improve our Tomographic results.

4. THE QUALITY OF DOPPLER TOMOGRAPHY

The quality of Doppler tomography depends on five basic parameters: the optimal phase resolution $\delta\phi$, the signal-to-noise ratio S/N of the data, the optimum efficiency ϵ of the spectrograph, the photon collection area A and the quantum efficiency Q_{eff} of the detector. To understand the effect of each parameter we will use here our observations of U Geminorum as an example.

The optimum phase resolution is defined as $\Delta\Phi = c/v(1/2\pi R)$, where c is the velocity of light, v is the orbital velocity of the area of the Doppler map that is of interest, and R is the spectral resolution given by $R = \lambda/\Delta\lambda$ (Spruit 1988). If the observed phase bins are larger than these value, there will be no gain in map quality. Since the optimal resolution is inversely dependent on the velocity and the spectral resolution, we take here two areas of interest as examples: one at high velocities, v=1000 km s^{-1}, (e.g., the inner regions of the disk), and another at low velocities v=310 km s^{-1} (e.g., near the L_1 point). For our resolution of R = 18,000 we obtain $\Delta\Phi$=0.0026 for the high velocity and $\Delta\Phi$=0.0085 for the low velocity. We want to compare these values with the observed phase bins. These are given simply by $\Delta\Phi_{obs} = \Delta t/P_{orb}$, where P_{orb} is the orbital period of the binary and Δt is the exposure time (both in the same units). For U Gem, the orbital period is about 15,285 s. Since the exposure time of our spectra was 600 s, the observed phase resolution is $\Delta\Phi_{obs}$=0.0392, a value much higher than the optimal phase resolutions derived for the high and low velocity regions. The optimal exposure time for the former would be about t = 40 s, a factor of 15 shorter than our actual exposure time. We have therefore smeared our velocity boxes in the phase direction by this factor. In other words, we will need about 400 exposures per orbital period to keep the best map boxes at the high velocity region with our given spectral resolution.

However, keeping the optimal phase resolution may result in an unacceptable S/N ratio. This is a fundamental parameter for we want to keep the quality of the velocity boxes. For example, if we want to construct a map with an error of only 1% we need S/N $\sim$ 100. The signal to noise ratio is given by

$$S/N = (948 \times 10^{-V/2.5}\, \epsilon\, A\, \Delta x\, Q_{eff}\, t)^{1/2}$$

(Levine & Chakrabarty 1994), were V is the visual magnitude; ϵ is the combined transmission of the atmosphere, telescope and spectrograph; A is the collecting area of the telescope; Δx is the CCD pixel resolution in Åpixel; Q_{eff} is the quantum efficiency of the detector in electrons per photon and t is the integration time in seconds. The S/N ratio for our observational setup ($\epsilon = 0.06[echelle + telescope]$); $A = 31,416\ cm^2$; $\Delta x = 0.13$ Å /pixel; $Q_{eff} = 0.6$ and $t = 600\ s$ is

$$S/N = 373 \times t^{1/2}(10^{-V/2.5})^{1/2}\,,$$

which for V = 14.0 (U Gem continuum at quiescence), will yield $S/N = 14.5$. Figure 4 shows one of our Hα spectra in a velocity scale taken near orbital phase 0.75. The spectrum shows the typical double profile and wings extending up to 1000 km s^{-1}. The S/N ratio near the wings is around 14 and reaches around 28 at the top of the double-line. Both the calculated and the observed S/N ratio are in good agreement, although we must point out that the derived S/N ratio from observations does not come from the visual and therefore the comparison is only a first order approximation. We have, in fact, under-

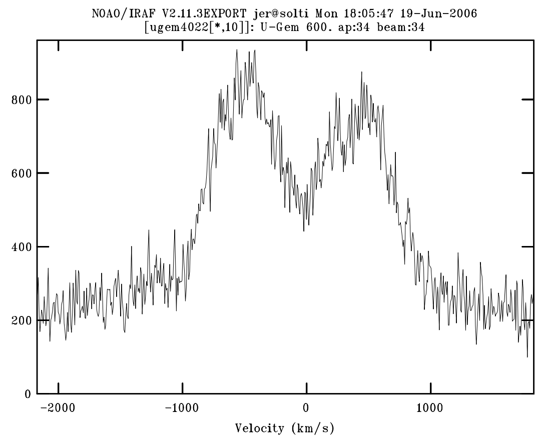

Fig. 4. Hα spectrum near orbital phase 0.75. The separation of the peaks is ~ 19.5 Å or 890 km s^{-1}.

exposed our spectra by about a factor of 14 for the set lower limit of $S/N = 100$.

5. IMPROVEMENT WITH LARGER TELESCOPES AND MORE EFFICIENT SPECTROGRAPHS

We come now to the question of whether we can reach the optimal phase resolution with a reasonable S/N ratio with larger telescopes and more efficient instruments and whether it is possible to obtain high quality Doppler tomography with high dispersion spectroscopy. We consider two cases: an echelle-type spectrograph and a medium spectral resolution, high-efficiency instrument like ESOPO (Echevarría et al. 2006). We approach the problem by following our example on U Gem. In the case of the echelle spectrograph we have calculated that the optimal phase resolution for velocities around 1000 km s^{-1} implies an exposure time $t = 40$ s. For an ESOPO-type instrument we expect to achieve $\epsilon = 0.30$ and $R = 5,000$. Therefore the optimal phase resolution for the same high velocity is $\Delta\Phi$=0.0094, which gives an optimal exposure time of $t = 145$ s. If we take $V = 14.0$ mag and $t = 145$ s then we are left with five working variables: the efficiency ϵ, the telescope collecting area A, the CCD pixel resolution Δx, the quantum efficiency Q_{eff} of the detector and the exposure time t. At these wavelengths modern CCDs yield $Q_{eff} \sim 0.9$ so basically S/N will be a function of ϵ, the collecting area A (or equivalently $\pi(D/2)^2$, were D is the diameter of the telescope) and to the CCD pixel resolution Δx (or equivalently to the spectral resolution $R = 2,350/\,\Delta x$, where we have taken Δx=0.13 Åpixel, and an element of spectral resolution as 2.3 pixels at visual wavelengths.

TABLE 1

THE S/N RATIO FOR A SAMPLE OF LARGER TELESCOPES WITH DIFFERENT SPECTROGRAPHS

S/N[a]	S/N[b]	D (m)	Telescope
5	37	2.1	SPM
15	121	6.5	SPM
23	186	10	GTC
46	373	20	M-20
69	560	30	TMT
97	783	42	ELT

[a]Echelle-type spectrograph.

[b]ESOPO-type spectrograph.

This results in a signal-to-noise ratio of

$$S/N = 2.0\,D\,(t\,\epsilon/R)^{1/2}\,.$$

Some examples of the S/N that could be obtained for U Gem at quiescence, with larger telescopes for both an echelle-type spectrograph ($\epsilon = 0.06$; $R = 18,000$, $t = 40$ s) and an ESOPO-type spectrograph ($\epsilon = 0.30$; $R = 5,000$, $t = 145$ s) are shown in Table 1 for comparison. We have included the 6.5-m telescope project for SPM, as well as other large telescope projects.

6. CONCLUSIONS

It is evident from Table 1 that in order to take full advantage of high resolution spectroscopy to produce high quality maps at high velocities, we would need very large telescopes indeed. Even for projects like the GTC, which are equivalent to the working Keck Telescopes, the errors in the high velocity boxes will be of the order of 5 percent. On the other hand, using intermediate dispersion with higher efficiency instruments might be a good solution to achieve our goal, although we would lose resolution in the high velocity boxes.

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