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Evolution and Outbursts of Cataclysmic Variables

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Abstract

Mass transfer and accretion are very important to understand the evolution and observational properties of cataclysmic variables (CVs). Due to the lack of an accretion disk, eclipsing profiles of polars are the best source to study the character of mass transfer in CVs. By analyzing long-term photometric variations in the eclipsing polar HU Aqr, the property of mass transfer and accretion are investigated. The correlation between the brightness state change and the variation of the ingress profile suggests that both the accretion hot spot and the accretion stream are produced instantaneously. The observations clearly show that it is the variation of mass transfer causing the brightness state changes that is a direct evidence of variable mass transfer in a CV. It is shown that it is the local dark-spot activity near the L_1 point to cause the change of the mass transfer rather than the activity cycles of the cool secondary star. Our results suggest that the evolution of CVs is more complex than that predicted by the standard model and we should consider the effect of variable mass accretion in nova and dwarf nova outbursts.

Keywords: cataclysmic variables - polars - photometry - individual: HU Aqr, DP Leo, MN Hya, and V2301 Oph.

1 Introduction

Cataclysmic variables (CVs) are semi-detached binaries where a low-mass (spectral types of K and M) component star transfers mass to a white dwarf (e.g., Warner 1995). According to the standard theory of CVs, the evolution of long-period ($P > 3$ hours) CVs are driven by angular momentum loss (AML) via magnetic braking (MB), and the "period gap" (the apparent scarcity of CVs in the period range from 3 to 2 hours) was explained as the cessation of the MB at the period of 3 hours when the secondary component becomes completely convective (e.g., Rappaport et al. 1983; Spruit & Ritter 1983). CVs below the "period gap" are governed by gravitational radiation. CVs as a mass transferring binary, the AML should keep the secondary filling the critical Roche lobe and transferring mass to the white dwarf continuously. In this way, CVs will evolve from a higher mass secondary with longer period to a lower mass secondary with shorter period.

Mass transfer and accretion in CVs are very important to understand their evolution and observational properties (e.g., the novae and dwarf-novae outbursts). Most CVs (e.g., polars and some dwarf novae and nova-like CVs) usually show brightness changes in high state, intermediate and low states. The most possible reason to cause these changes is the variation of mass transfer. However, direct evidence is lacking because of the influence of an accretion disk in a normal (non-magnetic) CV.

In a polar (magnetic CV), the magnetic field of the white dwarf is very strong to prevent the formation of an accretion disk (e.g., Giovannelli & Sabau-Graziati 2012). The transferred material from the secondary is quickly and directly accreted onto the white dwarf. During the eclipses, light components from the accretion stream and spot on the white dwarf can be isolated. Therefore, eclipsing polars can provide invaluable information on the character of mass transfer. The changes of eclipsing profiles directly reflect the variations in the mass-transfer rate. The results will shed light on our understanding of several key astrophysical problems such as the high and low brightness state changes and dwarf nova outbursts. However, only a few polars were monitored photometrically including the brightest polar AM Her (e.g., Hessman et al. 2000; Kafka & Honeycutt 2003, 2005; Wu & Kiss 2008), no eclipsing polars were monitored for a long time (e.g., up to several years) before.

On the other hand, the eclipse times of eclipsing polars can be determined with a high precision because the accretion stream and the hot spot on the white dwarf can be isolated during the eclipses. Very small-amplitude cyclic changes in the observed-calculated (O-C) diagram can be detected. Therefore, they are also good targets to search for planets and brown dwarfs orbiting CVs by analyzing the light travel time effect. Some substellar objects were recently discovered to be orbiting the polars DP Leo and HU Aqr (Qian et al. 2010a, 2011). By using the same method, planets orbiting other evolved binaries were discovered. Some examples discovered by our group are those orbiting the detached white-dwarf binaries QS Vir and RR Cae (Qian et al. 2010b, 2012a) and the subdwarf B-type binary NY Vir (Qian et al. 2012b).

2 Targets and Observations

We have selected ten eclipsing polars, DP Leo, EP Dra, V2301 Oph, EK UMa, HU Aqr, UZ For, V1432 Aql, MN Hya, V1309 Ori, and SDSS J015543.40+002807.2, for monitoring photometrically. We monitored those sample stars since 2009 by using the 2.4-m and 1.0-m telescopes at Yunnan observatories in China and the 2.15-m Jorge Sahade telescope at Complejo Astronomico El Leoncito (CASLEO), San Juan, Argentina. More than 100 eclipse profiles of the selected polars were observed. The eclipse profile for the eclipsing polar, V2301 Ophshown in Fig. 1. It was obtained on Feb. 15, 2012 by using the 2.4-m telescope in Lijiang observational station of Yunnan observatories. During the observation, no filters were used.

Among the selected eclipsing polars, we pay more attention to HU Aqr. It is one of the brightest eclipsing polars at both optical and X-ray wavelengths. This polar is a total eclipsing binary with an orbital inclination of $i = 87°$ and has only one accretion pole (e.g., Schwope et al. 2001). All these make it the most ideal target to investigate the properties of mass transfer through the long-term photometry. We have monitored it since 2009 and nearly 70 eclipse profiles were obtained.

3 Direct Evidence for Mass Transfer and Accretion

Two of white-light eclipse profiles of HU Aqr obtained at high and low brightness states are shown in Fig. 2. As shown in the figure, the eclipses start with the limb of the red-dwarf component eclipsing the hot spot (accretion region), and the primary is also eclipsed nearly at the same time. Then the accretion stream is the dominant source of the brightness with a small contribution of the secondary, and the distortion in the ingress profile is visible. Finally, only the red dwarf is visible and provides a constant contribution at the bottom of the eclipse.

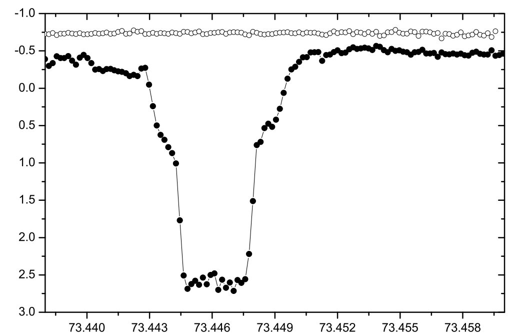

Figure 1: White-light photometric observations of V2301 Oph obtained on Feb. 15, 2012 by using the 2.4-m telescope in Lijiang observational station of Yunnan Observatories. Solid dots refer to the magnitude differences between V2301 Oph and the comparison star, while open circles to those between the comparison and the check stars.

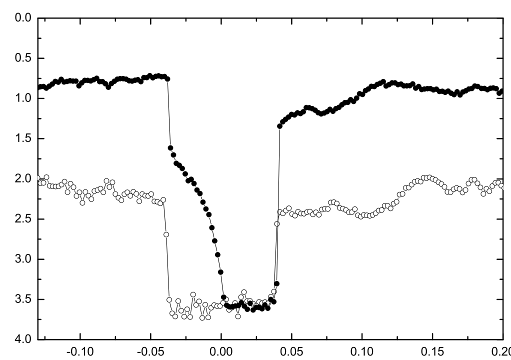

Figure 2: Comparison of two eclipse profiles for HU Aqr at high and low brightness states, respectively. The two eclipse profiles were obtained in 2011 by using the 2.4-m telescope in Yunnan observatories.

The sequence of the egress process is approximately reversed. As displayed in Fig. 2, the egress profile of HU Aqr is rather stable. Therefore, the mid-egress times were used to detect two planetary objects orbiting this binary star by analyzing the light travel time effect (Qian et al. 2011) and the new eclipse times will be used to revise the parameters of the circumbinary planets.

As shown in Fig. 2, when HU Aqr is at a high brightness state, the distortion in the ingress profile is visible. These properties suggest that there is an accretion stream from the secondary to the white-dwarf component and at the same time we see a hot spot on the white dwarf. Both the existences of the accretion stream and the hot spot indicate a high mass accretion rate at high brightness state.

On the other hand, at a low brightness state, the distortion in the ingress profile disappeared and the eclipse profiles are symmetric. These can be explained as the results that no hot spots on the white dwarf and no accretion streams are seen between the component indicating that no mass transfers and accretions between both components. The brightness variation is correlated with the change of the eclipse profile suggesting that both the hot spot and the accretion stream are produced instantaneously. This is a direct evidence of variable mass transfer and accretion in the CV.

Two eclipse profiles at high brightness states are plotted in Fig. 3. The two eclipse profiles were observed on May 29 and 31,2011 with the 2.15-m Jorge Sahade telescope in Argentina. As displayed in the figure, both the brightness before the eclipse and the ingress profile are variable in two days. Other two eclipse profiles obtained in 2010 by using the 1.0-m telescope in Yunnan observatories are displayed in Fig. 4. It is shown in the figure that HU Aqr is on the way from a high state to a low state indicating that the rate of mass transfer is decreasing.

4 Discussion and Conclusions

The observations in previous section give a direct evidence for variable mass transfer and accretion in CVs. The orbital period of HU Aqr is about 2.08 hours, just below the CV period gap. Non-magnetic CVs with orbital periods in this range are usually dwarf novae (DN). Two dwarf novae, IR Com and DV UMa, have the nearly same orbital period as that of the eclipsing polar HU Aqr. They show DN outbursts (a sudden increase of brightness up to 2-7 magnitudes) at usually irregular intervals (Nogami et al., 2001). Their DN outbursts are explained as the disc instability (Cannizzo 1993). However, it is not clear that the outbursts are pure disc phenomena that occur without some contribution of variable mass transfer from the secondary (Livio & Verbunt, 1988; Duschl & Livio, 1989). Our conclusions suggest that we should consider the contribution of mass transfer in the model of CV outbursts (e.g., Cannizzo 1993). The evolution of CVs may be more complex than that predicted by the standard model.

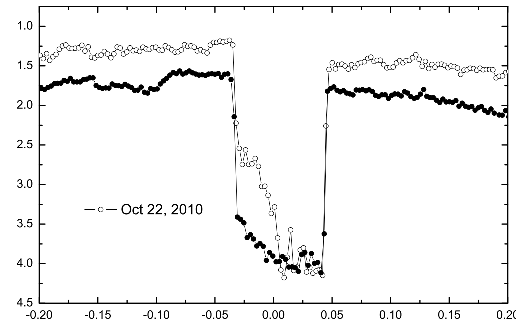

Figure 3: White-light eclipse profiles observed with the 1.0-m telescope in Yunnan observatories. Open circles refer to the data obtained on Oct. 22, 2010, while solid dots to those obtained on Oct. 30.

Some physical mechanisms, such as irradiation-driven mass transfer and star-spots cause (e.g., Wu et al., 1995; Livio & Pringle 1994), have been proposed to explain the changes of mass transfer in CVs. To solve this question, we analyzed the brightness variation around phase 0.5. It is discovered that the brightness from phase 0.3 to 0.65 usually shows a large dip at low states when the mass transfer rate is very low. Two of the light curves obtained at low states are shown in Fig. 5 where a large dip is seen around phase 0.5. These brightness dips can be explained by the presence of dark spots near the L_1 point on the cool secondary star. This conclusion indicates that it is the coverage of dark spots near L_1 point that produce the decrease of the mass transfer rate.

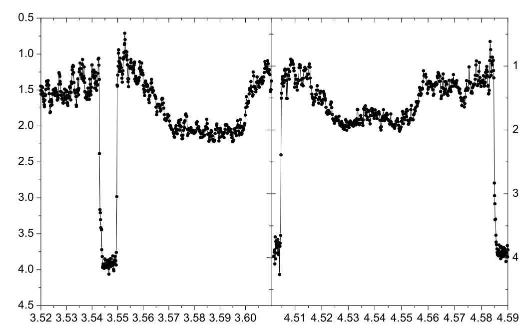

Figure 4: Two light curves of HU Aqr observed at low brightness states with the 2.15-m Jorge Sahade telescope in Argentina. It is shown that the brightness around phases 0.5 shows a large dip. The light curve in the left was obtained on Nov. 11, 2011, while that in the right was obtained on Nov. 12.

At the bottom of the eclipse, all of the hot spot, the white dwarf, and the accretion stream are eclipsed by the secondary. Only the red-dwarf component is visible and provides a constant contribution. Therefore, it is the only chance to measure the brightness change of a mass donor in a CV. A cyclic variation in the brightness of the secondary is discovered that can be explained as the dark-spot activity cycle. It is the first time to detect an activity cycle for a fast-rotating mass donor in a CV. Our results reveal that the variable mass accretion is not caused by magnetic activity cycles of the fast-rotating red dwarf.

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DISCUSSION

K. REINSCH: Which filters did you use for your photometry? Could you see a colour dependence in the orbital variation as would be expected for a light curve contribution originating from the secondary?

QIAN SHENGBANG: Since we need high time resolution for our data, the exposure time is only a few seconds. Therefore, no filters were used during the observations.