PROCEEDINGS OF SCIENCE

Investigating Spiral Structures in Accretion Disks of Cataclysmic Variables through Multicolor Eclipse Observations

GU YUCHENG,[a,*] MAKOTO UEMURA[a] and RYOSUKE SAZAKI[a]

[a] *Graduate School of Advanced Science and Engineering, Hiroshima University,*
1-3-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8526, Japan

E-mail: guyuchen@astro.hiroshima-u.ac.jp

The mechanisms of mass accretion and angular momentum transport in accretion disks remain uncertain. Although magneto-rotational instability has been successful in theoretical explanations, obtaining observational evidence remains challenging. Numerical simulations have predicted asymmetric spiral shock waves in disks, suggesting that material in the disk loses angular momentum after impacting the shock waves. Spiral structures were later observed during outbursts in multiple objects, though the origin remains debated. It may not be shock waves, but rather tidal distortions in the disk. If the structures are caused by shock waves, they would exhibit significantly higher temperatures than the surrounding disk. We conducted multi-wavelength eclipse observations of cataclysmic variables to estimate the temperature of the spiral structures. We constructed a 3D accretion disk and Roche lobe model, incorporating spiral structures with adjusted temperature distributions. By fitting the model to the observed light curves, the possible location and temperature of spiral patterns can be inferred. Eclipse light curves of UU Aqr were obtained through simultaneous V- and J-band observations using the Kanata telescope at Hiroshima University. In the V-band, the eclipse ingress was slower than predicted, while in the J-band it began earlier, suggesting a deviation from the temperature distribution of the standard disk model. On the other hand, no sign of high-temperature spiral structures was identified in the eclipse profile.

87th Fujihara Seminar The 50th Anniversary Workshop of the Disk Instability Model in Compact Binary Stars (DIM50TH2025)
22-26 September 2025
Tomakomai, Japan

---

[*] Speaker

PoS(DIM50th2025)041

1. INTRODUCTION

Dwarf novae are close binary systems consisting of a white dwarf primary and a low-mass companion star. Material flowing from the companion forms an accretion disk around the primary before accreting onto it [1]. The mass accretion toward the center of the disk has been proposed to occur via viscous angular momentum transfer driven by magneto-rotational instability [2, 3], although obtaining direct observational evidence for this process remains challenging. Another hypothesis is that spiral shock waves within the accretion disk may facilitate angular momentum transport [4, 5]. Steeghs (1997) [6] observed a spiral structures in the dwarf nova IP Peg, which was later reproduced in simulations by Steeghs (1999) [7]. If the spiral structures correspond to shock waves, their temperatures are expected to be significantly higher than that of the surrounding disk. In contrast, if the structures are merely distortions of the disk due to tidal deformation [8], no substantial temperature difference would arise.

In this study, we perform simultaneous optical and near-infrared observations of the novalike object UU Aqr to investigate the temperature distribution in the disk, and thereby examine this issue. In Section 2, we briefly describe our observations. Section 3 presents our model. In Section 4, we show the results of fitting the model to the observed light curves. We discuss and conclude our findings in Sections 5 and 6.

2. OBSERVATIONS

Observations of the eclipse of UU Aqr were performed using the 1.5-meter Kanata Telescope equipped with the Hiroshima University Optical and Near-infrared Camera (HONIR). Data were obtained in the V-band (optical) and J-band (infrared) on 13 November 2024. The mid-eclipse time was calculated based on the HJD ephemeris provided by Boyd (2023) [9]. Our observations covered approximately half of the orbital period (~ 2 hours), centered on the mid-eclipse.

3. MODEL

We constructed a three-dimensional model of eclipse light curves. Figure 1 presents the three-dimensional configuration of the model. The accretion disk and the Roche lobe of the companion star were represented using point clouds. The structure of the spiral patterns was modeled following the formulations and parameters of Hachisu et al. (2004) [10] and Maehara et al. (2007) [11]. In Figure 1, the outermost temperature of the accretion disk was set to 5000 K, and the temperature of the shock pattern was defined to be eight times that of the disk. An occlusion detection algorithm was employed to compute the self-occultation within the accretion disk, while a collision detection algorithm was used to evaluate the obscuration of the disk by the companion's Roche lobe. The flux from the accretion disk was then calculated by summing the flux from each point that remained visible along the line of sight. We consider only the radiation originating from the accretion disk because it dominates during high and intermediate states of UU Aqr and the contribution from the other components, such as the hot spot and secondary star is negligible [12].

Figure 2 shows the light curves calculated with the two models: 1) the model which only includes the accretion disk without spiral patterns, called the disk model, indicated by the blue curve, and 2) the model which includes both the disk and spiral patterns, called the disk+spiral model, indicated by the orange curve. At the ingress of the eclipse, the disk+spiral model produces a rapid drop in brightness compared with the disk model, in both V- and J-band. After mid-eclipse, the spirals alter the flux-recovery behavior, producing a slower initial rise followed by a faster increase at later phases, while the timing of the eclipse egress remains nearly unchanged. Their presence makes the profile of the light curve asymmetric in the disk+spiral model. At the mid-eclipse, the spiral pattern produces a shallower eclipse in the V-band, while it makes a deeper eclipse in the J-band. This is due to their different sensitivities to the high temperature spiral pattern, demonstrating the detectability of its temperature from our multi-band photometry.

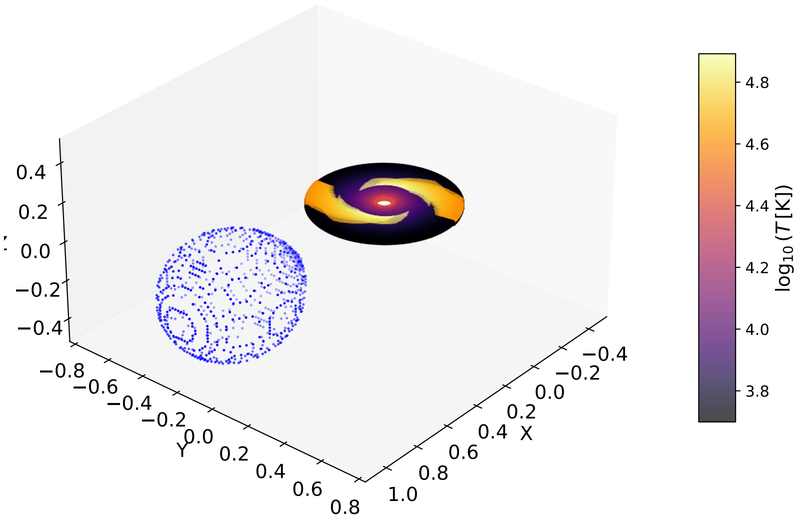

Figure 1: Accretion disk and spiral structures in our model. The colors represent the temperature distribution across the disk. The outermost temperature of the disk is 5000 K, and the temperature of the spiral pattern is assumed to be eight times that of the disk.

4. RESULT

We fitted the observed light curves in both the V- and J-band using two models: the disk model and the disk+spiral model. The eclipse light curves are calculated using a three-dimensional model characterized by a mass ratio $q = 0.4$, an orbital inclination of $i = 76°$ [13], and an accretion disk radius fixed at $R_\mathrm{d} = 0.57\,R_{\mathrm{L}1}$ [14]. The spiral structures are introduced with a fixed geometry, with their azimuthal orientation set to approximately 100°, as illustrated in Figure 1. These parameters define the global geometry of the system, while the outermost temperature of the disk and the temperature factor of the spiral pattern are estimated from the data. The results are presented in Figure 3, where the observational data are shown as blue points with error bars, and the best-fitted models are indicated by the solid curves. In the out-of-eclipse phase, the light curves exhibit a slightly brightening trend, fitted with a linear function of time. Although the disk model (the red curve) yields a slightly lower temperature (4983 ± 46 K) at the outer edge of the disk than the disk+spiral

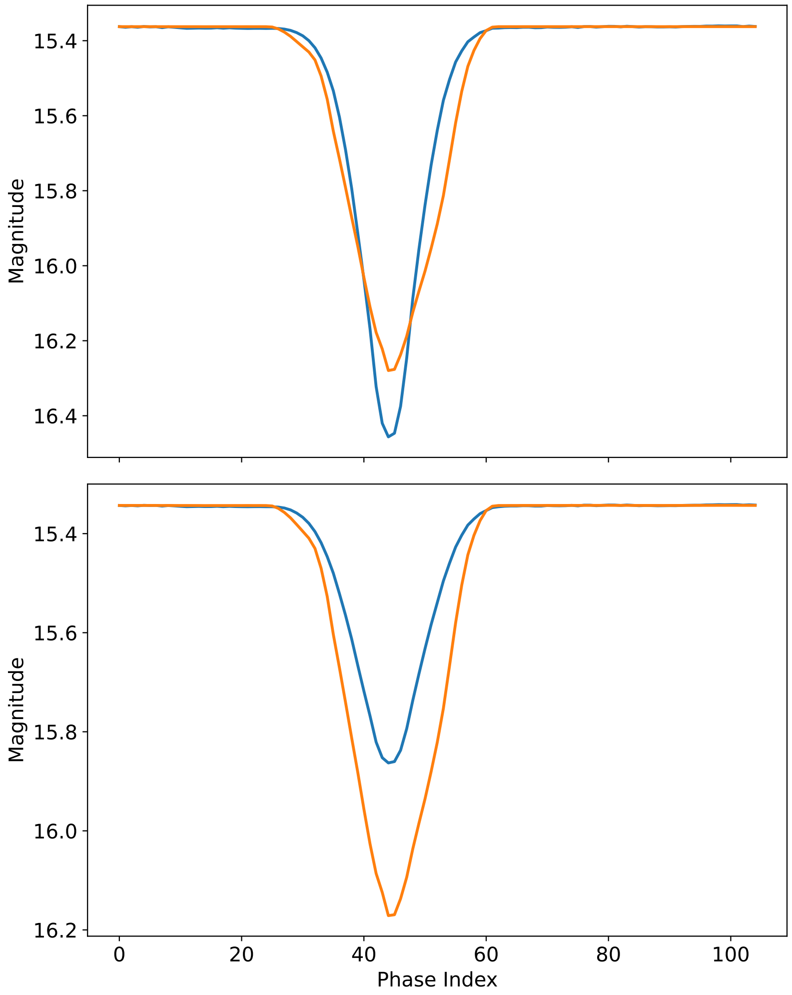

Figure 2: Eclipse light curves from the disk model and the disk+spiral model are shown, with the V-band on the upper panel and the J-band on the lower panel. The blue and orange solid curves represent the disk model and the disk+spiral model, respectively.

model (the orange curve, 5555 ± 66 K), the overall morphology of the resulting light curves shows no meaningful difference between the two models. This is because the spiral pattern has a temperature slightly lower than that of the surrounding disk, at 0.95 ± 0.04 times the disk temperature.

As shown in Figure 3, both in the V- and J-band, the observed light curves exhibit a more rapid decrease at the ingress of the eclipse compared to the models. Since most of the eclipse profile can be explained by the accretion disk without spiral patterns, as shown in Figure 3, this flux drop just before the ingress suggests an additional emitting region located outside the disk. Based on the disk+spiral model, we subsequently introduced a small localized emission region on the outer side of the disk at an azimuthal angle of 270°. The relative position of this emission region within the system is illustrated in Figure 4. We fitted the new model, hereafter referred to as the disk+spiral+spot model, to the observed light curves. The new results are shown in Figure 5 with the purple curve, while the previous results with the disk+spiral model are shown with the orange curve. As can be seen, the modified model reproduces the rapid brightness decrease observed at

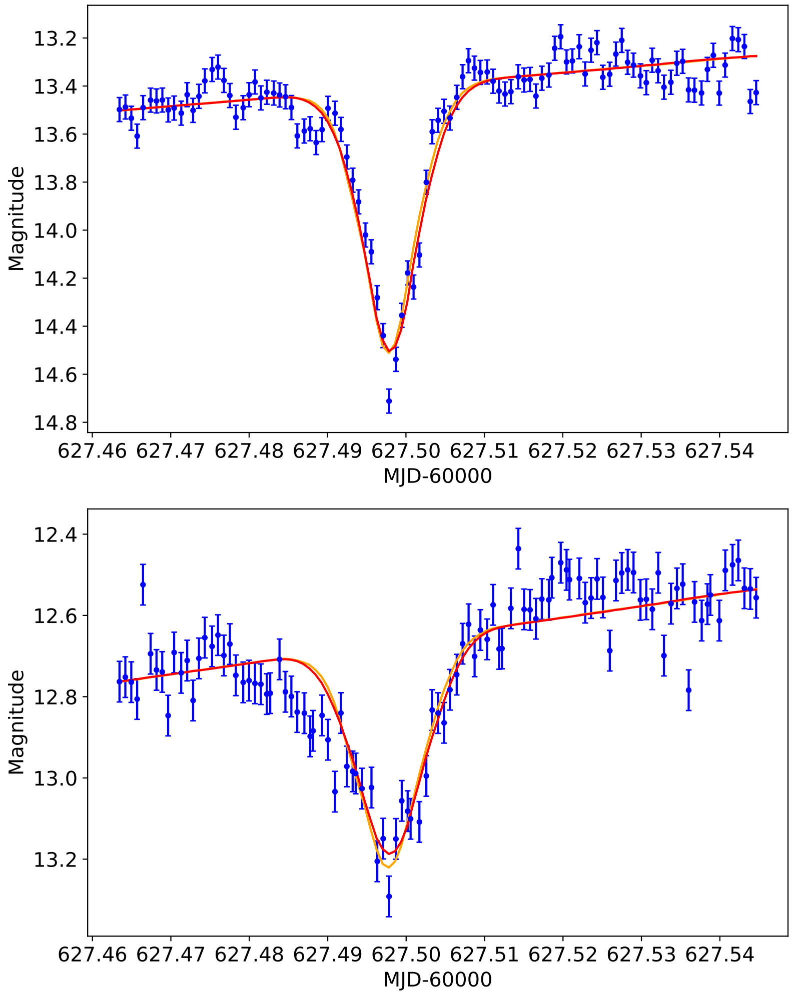

Figure 3: Best-fitted V- and J-band light curves using the disk model and the disk+spiral model. The upper and lower panels correspond to the V- and J-band, respectively. Blue points denote the observational data, the red curve represents the disk model, and the orange curve shows the disk+spiral model

the eclipse ingress. This emission source exhibits a temperature 2.35 ± 0.05 times higher than that of the surrounding disk, whereas the spiral structures display no discernible temperature contrast relative to the disk.

5. DISCUSSION

A rapid drop in brightness during eclipse ingress have also been reported in previous studies when UU Aqr was observed in an intermediate state with $V = 12.8$—15.5, indicating that this behavior is likely a universal feature of the system [14, 15]. Doppler tomographic studies of other cataclysmic variables has also revealed an emitting region located opposite the hot spot [16], in a position comparable to the additional emission component assumed in our analysis. While the nature of this emitting region is unclear, our results suggest that this emitting region is characterized by a high temperature (~ 9395 K) relative to the outer edge of the disk (~ 3998 K). In contrast, the

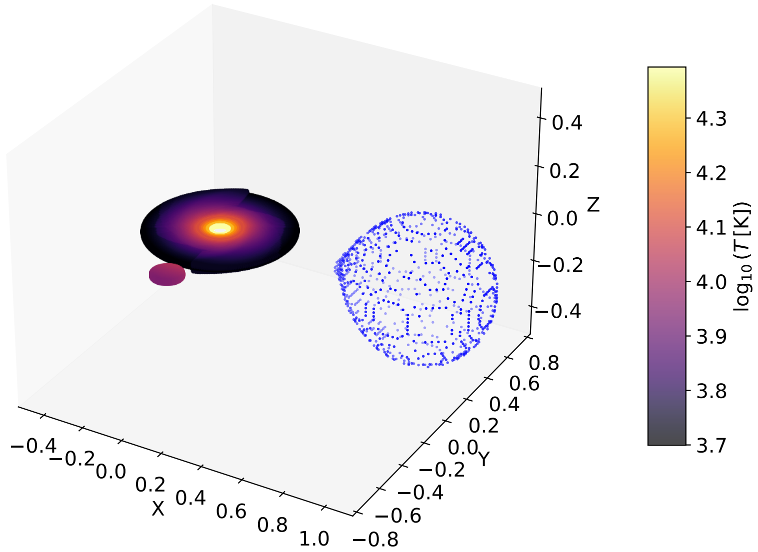

Figure 4: Temperature distribution of the accretion disk and the additional emission region optimized to reproduce the observed light curves of UU Aqr.

temperature of the spiral structures is comparable to that of the surrounding disk, and hence our result supports that these spiral structures are driven not by a shock, but by a tidal deformation.

6. CONCLUSION

We constructed an accretion disk model incorporating spiral structures to simulate the eclipse light curves of the corresponding binary system. The spiral structures having high-temperature deform the eclipse light curve, particularly near ingress and egress, and modify the eclipse depth. As a result, both the V- and J-band light curves exhibit noticeable asymmetry. We conducted simultaneous V- and J-band observations of UU Aqr. The standard disk model alone cannot account for the rapid brightness drop observed during eclipse ingress, whereas introducing an additional emitting region successfully reproduces this initial decline. Our results indicate that the extra region is relatively hot, while the spiral structures themselves remain cool, providing no evidence in favor of the shock-wave hypothesis.

References

[1] B. Warner, *Cataclysmic variable stars*, vol. 28, Cambridge University Press (2003).

[2] S.A. Balbus and J.F. Hawley, *A powerful local shear instability in weakly magnetized disks: I. linear analysis*, in *Bulletin of the American Astronomical Society, Vol. 22, p. 1209*, vol. 22, p. 1209, 1990.

[3] S.A. Balbus and J.F. Hawley, *Instability, turbulence, and enhanced transport in accretion disks*, *Reviews of modern physics* **70** (1998) 1.

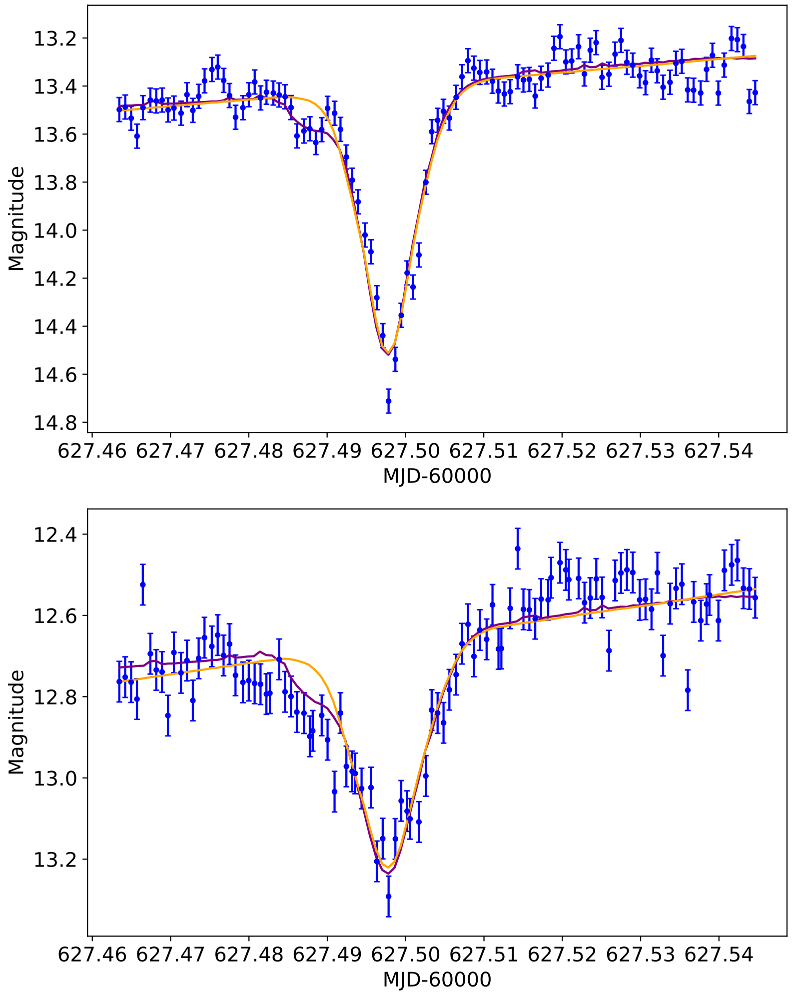

Figure 5: Best-fitted V- and J-band light curves using the disk+spiral model and the disk+spiral+spot model. The upper and lower panels correspond to the V- and J-band, respectively. Blue points represent the observational data, the orange curve denotes the disk+spiral model, and the purple curve represents the disk+spiral+spot model

[4] K. Sawada, T. Matsuda and I. Hachisu, *Spiral shocks on a roche lobe overflow in a semi-detached binary system*, *Monthly Notices of the Royal Astronomical Society* **219** (1986) 75.

[5] H. Spruit, *Stationary shocks in accretion disks*, *Astronomy and Astrophysics (ISSN 0004-6361), vol. 184, no. 1-2, Oct. 1987, p. 173-184.* **184** (1987) 173.

[6] D. Steeghs, E. Harlaftis and K. Horne, *Spiral structure in the accretion disc of the binary ip pegasi*, *arXiv preprint astro-ph/9708005* (1997) .

[7] D. Steeghs and R. Stehle, *On the observability of spiral structures in cataclysmic variable accretion discs*, *Monthly Notices of the Royal Astronomical Society* **307** (1999) 99.

[8] G. Ogilvie, *Tidally distorted accretion discs in binary stars*, *Monthly Notices of the Royal Astronomical Society* **330** (2002) 937.

[9] D. Boyd, *Long-term study of changes in the orbital periods of 18 eclipsing sw sextantis stars*, *arXiv preprint arXiv:2307.03677* (2023) .

[10] I. Hachisu, M. Kato and T. Kato, *Detection of two-armed spiral shocks on the accretion disk of the eclipsing fast nova v1494 aquilae*, *The Astrophysical Journal* **606** (2004) L139.

[11] H. Maehara, I. Hachisu and K. Nakajima, *Photometric observation and numerical simulation of early superhumps in bc uma during the 2003 superoutburst*, *arXiv preprint astro-ph/0611519* (2006) .

[12] R. Baptista, J.E. Steiner and K. Home, *Multicolour eclipse studies of uu aquarii—ii. the accretion disc*, *Monthly Notices of the Royal Astronomical Society* **282** (1996) 99.

[13] M. Diaz and J.E. Steiner, *Spectroscopy of the cataclysmic variable uu aqr*, *Astronomical Journal (ISSN 0004-6256), vol. 102, Oct. 1991, p. 1417-1422.* **102** (1991) 1417.

[14] S. Vrielmann and R. Baptista, *Uu aqr from high to low state*, *Astronomische Nachrichten: Astronomical Notes* **323** (2002) 75.

[15] J. Robertson, R. Honeycutt, A. Henden and R. Campbell, *Orbital light curves of uu aquarii in stunted outburst*, *The Astronomical Journal* **155** (2018) 61.

[16] V. Neustroev, S. Zharikov and N. Borisov, *Voracious vortexes in cataclysmic variables-a multi-epoch tomographic study of ht cassiopeia*, *Astronomy & Astrophysics* **586** (2016) A10.