PROCEEDINGS OF SCIENCE

On the Evolutionary Pathway of WZ Sge-type Dwarf Nova GOTO065054.49+593624.51

Hiromasa Hoke,[1] **Keisuke Isogai,**[2,3] **Yusuke Tampo,**[4,5] **Katsuki Muraoka,**[1] **Naoto Kojiguchi,**[2] **Tamás Tordai,**[6] **Tonny Vanmunster,**[7,8,9] **Stephen M.Brincat,**[10] **Franz-Josef Hambsch**[11,12,13] **and Daisaku Nogami**[1]

[1] *Department of Astronomy, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto, Kyoto 606-8502, Japan*

[2] *Okayama Observatory, Kyoto University, 3037-5 Honjo, Kamogata, Asakuchi, Okayama 719-0232, Japan*

[3] *Department of Multi-Disciplinary Sciences, Graduate School of Arts and Sciences, The University of Tokyo, 3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan*

[4] *South African Astronomical Observatory, PO Box 9, Observatory, Cape Town 7935, South Africa*

[5] *Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa*

[6] *Polaris Observatory, Hungarian Astronomical Association, Laborc utca 2/c, 1037 Budapest, Hungary*

[7] *Center for Backyard Astrophysics Belgium, Walhostraat 1A, B-3401 Landen, Belgium*

[8] *Center for Backyard Astrophycis Extremadura, e-EyE Astronomical Complex, 06340 Fregenal de la Sierra, Spain*

[9] *Vereniging voor Sterrenkunde (VVS) , Oostmeers 122 C, 8000 Brugge, Belgium*

[10] *Flarestar Observatory, San Gwann SGN 3160, Malta*

[11] *Bundesdeutsche Arbeitsgemeinschaft für Veränderliche Sterne (BAV) , Munsterdamm 90, 12169 Berlin, Germany*

[12] *Groupe Européen d'Observations Stellaires (GEOS) , 23 Parc de Levesville, 28300 Bailleau l'Evêque, France*

[13] *Vereniging Voor Sterrenkunde (VVS), Zeeweg 96, B-8200 Brugge, Belgium*

E-mail: hoke@kusastro.kyoto-u.ac.jp

ISSN 1824-8039. Published by SISSA Medialab.

PoS(DIM50th2025)045

We observed the dwarf nova system GOTO065054.49+593624.51 (hereafter GOTO0650), and classified its rebrightening behavior as type E and type B (type E means double superoutburst and type B means multiple rebrightenings). Based on the $O-C$ analysis of superhump maxima, we estimated its mass ratio and orbital period as $q = 0.073(9)$ and $P_{\mathrm{orb}} = 0.0625(2)$ d, respectively. These values support the idea that GOTO0650 may follow the standard evolutionary path of cataclysmic variables. However, this object showed an unusually large number of rebrightenings (11 events) and a prolonged active phase of approximately 100 days. To investigate the rebrightening models of systems with multiple rebrightening outbursts including GOTO0650, we conducted a statistical survey from the perspective of the average outburst cycle of rebrightening, defined as the time per rebrightening T_{reb} (d). Many of type B objects are in the range of $5 \leq T_{\mathrm{reb}} \leq 9$, suggesting that physical rebrightening mechanism may be common to type B objects. The T_{reb} of GOTO0650 is 8.89 d. GOTO0650 is within the normal range in terms of T_{reb}, so physical mechanisms may be common to at least type B objects and GOTO0650. There are two proposed models of the mechanism of rebrightening, the mass reservoir model and the enhanced mass transfer model. From prior research, T_{reb} might be linked to binary parameters such as a mass ratio. We examined whether there was any correlation between T_{reb} and parameters based on the two models. Both parameters based on the two models exhibited a correlation with T_{reb}. However, no significant differences were found between the correlations derived from the two models.

PoS(DIM50th2025)045

1. Introduction

Cataclysmic Variables (CVs) are close binary systems consisting of a white dwarf primary and a late main-sequence secondary, which fills its Roche lobe. Mass transfer from the secondary to the primary forms an accretion disk around the primary. Dwarf Novae (DNe), a subclass of CVs, show brightening events called outbursts and superoutbursts, explained by the thermal instability model and the thermal-tidal instability (the TTI model), respectively [1, 2].

The outburst is triggered when the accretion disk reaches the critical surface density due to mass transfer from the secondary. This causes the disk to transition from a cool state to a hot state. The hot disk exhibits high viscosity, enabling efficient angular momentum transfer between gas particles. The gas then falls onto the white dwarf at a higher rate than in quiescence. Moreover, it releases gravitational energy, causing an increase in luminosity observed as an outburst. In particular, the accretion disks of the SU UMa-type and WZ Sge-type dwarf novae, subclasses of DNe, reaches the 3:1 resonance radius in outburst. This triggers tidal instability, causing the disk to become elliptically deformed [3, 4]. This causes a brighter and longer-lasting outburst phenomenon called a superoutburst. The angular momentum is efficiently extracted from the disk during superoutburst. Superhump is a brightness variation of 0.1 to 0.3 magnitudes and has a period of a few percent longer than the orbital period. This period is known to vary throughout the superoutburst, and analyzing its period derivative (one of the methods of analysis is $O-C$ analysis) allows an empirical estimation of the mass ratio and orbital period.

Some SU UMa-type dwarf novae, WZ Sge-type dwarf novae, and low-mass X-ray binaries exhibit a phenomenon called rebrightening. After a superoutburst ends, a brightening event is observed several days later before the system returns to quiescence. WZ Sge-type dwarf novae can be classified into five types based on the light curve profiles of their superoutbursts and rebrightenings: (A) flat top, (B) multiple, (C) single, (D) no, and (E) double superoutburst. Earlier studies suggest the rebrightening types evolve in the order C → D → A → B → E as the system evolves [5]. However, the mechanisms behind these rebrightening outbursts and their potential correlation with binary evolution remain poorly understood. Proposed models for triggering rebrightening include the mass reservoir (hereafter MR) [6, 7], enhanced mass transfer (hereafter EMT) [8], and enhanced viscosity model [9]. The MR model posits that gas can remain in a region between the tidal truncation and the 3:1 resonance radii after an outburst. After the superoutburst, the accreting mass from the MR allows the disk to reach the critical density again, and triggers the rebrightening. The EMT model, on the other hand, involves a temporary increase in the mass transfer rate from the secondary irradiated by the hot disk and the primary in outburst. This causes the quiescent disk to reach critical density soon after the superoutburst, which is observed as a rebrightening. The enhanced viscosity model suggests that the viscosity after a superoutburst is higher than that in quiescence due to a superoutburst. That is why the accretion disk is more easily reaches critical density.

To distinguish these models, for objects exhibiting multiple rebrightenings, we define T_{reb} as the average outburst cycle of rebrightening. We then consider this parameter for both the MR and EMT models. We investigated the correlation between the observational parameter T_{reb} and the two models.

To investigate the validity of each model, statistical studies concerning rebrightenings are necessary. In 2024, the object GOTO0650 was discovered and exhibited highly characteristic rebrightenings. In this paper, we performed statistical analysis focusing on the cycle length of rebrightenings as a characteristic feature for objects showing multiple type-B rebrightenings of WZ Sge-type dwarf novae, including GOTO0650. Sec. 2 presents the observational results of GOTO0650 and the features of its rebrightenings. Sec. 3 discusses the results of our statistical analysis concerning the rebrightening feature and the rebrightening models.

2. GOTO065054.49+593624.51

2.1 Outburst propeties of GOTO0650

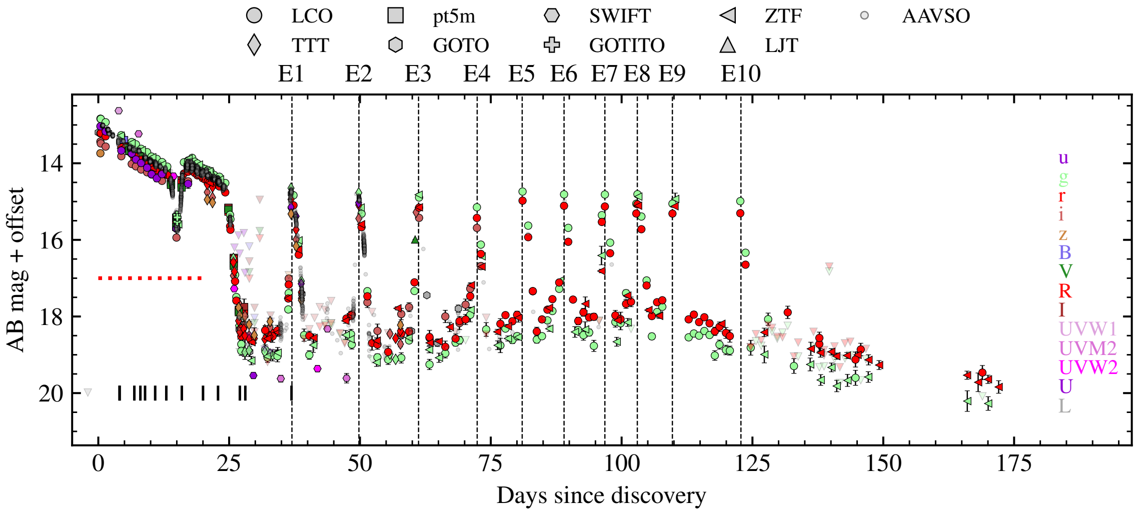

Figure 1: Lightcurve of GOTO0650 (Killestein et al (2025) [10]). End of superoutburst is about ∼ 25d since discovery. Vertical lines indicate times of rebrightening

GOTO065054.49+593624.51 was first discovered by the Gravitational-wave Optical Transient Observer ([11–13]) on 2024/10/4 03:36:36 UT [10, 14, 15]. The light curve in Fig.1 is quoted from Killestein et al (2025)[10]. We classified its rebrightening type as E and B based on the dip during the superoutburst, the growth of the ordinary superhump after the dip, and the multiple rebrightening outbursts. Killestein et al (2025)[10] reported that GOTO0650 showed an outburst amplitude of 8.5 mag and a spectrum with strong Balmer and weak He II emission lines. Moreover, Castro-Segura et al. (2025) [14] detected an oscillation of ≃ 148 s in the g-band in the gap between superoutburst and rebrightening. They interpreted this as the white dwarf spin period. Killestein et al (2025)[10] detected 10 rebrightenings but we detected one additional rebrightening between E1 and E2.

2.2 period variation of superhump

We conducted $O - C$ analysis for superhumps observed in GOTO0650. The data are based on the Variable Star Network [16](VSNET), the Variable Star Observers League of Japan (VSOLJ), the American Association of Variable Star Observers (AAVSO), the Las Cumbres Observatory

Global Telescope[17](LCOGT), the Zwicky Transient Facility[18](ZTF). Our data based on $O-C$ analysis are high quality during the stage B of the ordinary superhumps in the $O-C$ diagram. Therefore, we conducted quadratic fitting on the stage B range and obtained $P_{\rm sh} = 0.063231(21)$ d and $P_{\rm dot} = (\dot{P}_{\rm sh}/P_{\rm sh}) = 2.9(1.7)\times10^{-5}$. It is known that the average period change rate ($P_{\rm dot}$) of superhump stage B can be used to estimate a mass ratio q empirically. According to Kato (2015)[5], $q = 0.0043(9)\times P_{\rm dot}\times10^{5} + 0.060(5)$. Using the relation, we estimated $q = 0.073(9)$. For objects with $q \approx 0.073$, it is empirically known that $P_{\rm sh}$ is about 1% longer than $P_{\rm orb}$ [19]. Therefore, from its $P_{\rm sh}$, we estimated $P_{\rm orb} = 0.0625(2)$ d.

2.3 feature of rebrightening

We conducted a statistical survey of type B objects, including GOTO0650. GOTO0650 exhibits a significantly longer and larger number of rebrightenings (11 outbursts in ~100 days) compared to typical type B objects. For example, the representative type B object EG Cnc shows six rebrightenings over about 44 days [20].

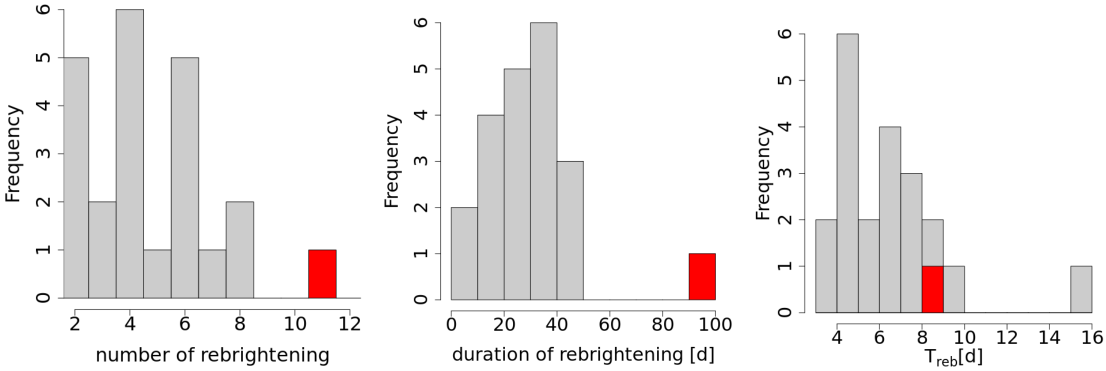

Figure 2: Histograms of N, $T_{\rm dur}$, and $T_{\rm reb}$ from left to right. The red bin represents GOTO0650.

Here we define $T_{\rm reb}$ as the average outburst cycle of the rebrightening outbursts. Let N be the number of rebrightening outbursts since the end of the superoutburst. We define $T_{\rm dur}$ as the rebrightening duration, measured from the end of the superoutburst to the peak of the last rebrightening outburst. Then $T_{\rm reb}$ can be expressed as $T_{\rm dur}/N$. According to our statistical survey presented in Fig. 2, most of type B objects including GOTO0650 have $T_{\rm reb}$ less than or equal to 10 d. From this perspective, GOTO0650 is predicted to share a common rebrightening mechanism with other type B objects.

3. discussion

3.1 mass ratio and evolutionary track

According to [21], the evolutionary path of dwarf novae is predicted as shown in Fig.3 [22, 23]. It has been questioned whether GOTO0650 follows this evolutionary path. In Sec. 2.3, we estimated the orbital period $P_{\rm orb}$ and mass ratio q of GOTO0650. Although the mass ratio is slightly larger than those of type E rebrightening objects, GOTO0650 is predicted to follow a typical evolutionary path within an error range [22]. Fig.3 shows the evolutionary path diagram color-coded according

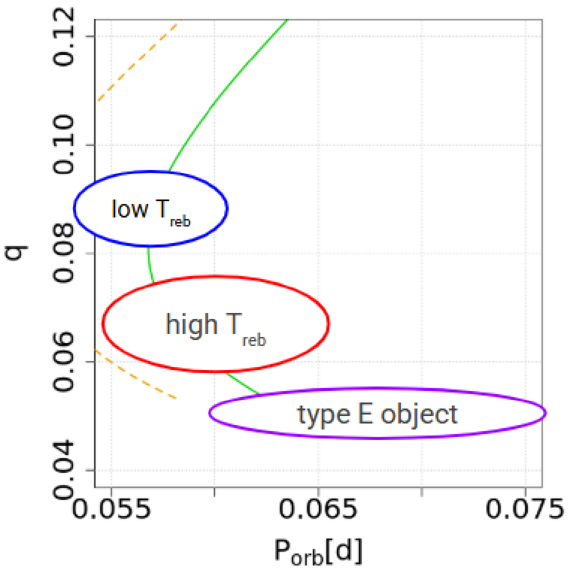

Figure 3: The schematic evolutionary state of type-B and type-E rebrightening objects. The orange and green lines represent theoretical evolution curve and evolutionary track best fitted to observational data, respectively.

to the magnitude of T_{reb} (low T_{reb} means $T_{\text{reb}} < 6$, and high T_{reb} means $T_{\text{reb}} > 6$). This suggests that the rebrightening profile evolves from short T_{reb} to long T_{reb}, and eventually type E, along the binary evolutionary track. This indicates that T_{reb} may be expressed as a function of binary parameters. Therefore, we investigate whether the two existing models (MR, EMT model) show a correlation with T_{reb}.

3.2 comparison of two rebrightening models

We consider that this T_{reb} represents the angular momentum extraction efficiency in the MR model and the enhanced mass transfer rate in the EMT model, making T_{reb} an observational indicator for each model. Here, we assume that T_{reb} can be expressed as a binary parameter when interpreting the rebrightening phenomenon in two existing models. In the following, we calculate the p-values for the relationship between T_{reb} and the binary parameters in each model.

3.2.1 MR model

As noted in Sec.1, the MR model suggests that there is a region that can accumulate gas outside the disk [6, 7]. Let M denote the mass the reservoir can accumulate. Since it has been shown [24] that the mass distribution of white dwarfs in cataclysmic variables is concentrated around 0.8 $M_\odot$, the inner and outer radii of the mass reservoir are assumed to be nearly constant across systems. Consequently, Kepler's law implies that the specific angular momentum in the mass reservoir is independent across systems. At this point, the number of rebrightening events is thought to be proportional to the total mass of the MR, meaning that it is proportional to the total angular momentum. Furthermore, the duration of the rebrightening phase is thought to be proportional to the angular momentum of the MR divided by the efficiency with which the angular momentum is extracted from it. Here, let L and $\dot{L}$ denote the angular momentum which system has and its time derivative, respectively. Thus, $T_{\rm reb} = T_{\rm dur}/N \propto (L/\dot{L})/L = \dot{L}^{-1}$ is thought to represent the efficiency of angular momentum extraction from the system. According to [25, 26], this angular momentum extraction efficiency can be expressed as $q^2/P_{\rm orb}$.

3.2.2 EMT model

As noted in Sec.1, this model proposes that irradiation of the secondary by the hot disk and the primary increases the mass transfer rate. Even after the superoutburst ends and a temporary quiescent state occurs, the increased mass transfer rate causes the disk to become thermally unstable again, observed as a rebrightening phenomenon [8]. According to [27],the irradiative flux on the secondary generated by the disk rebrightening is proportional to the binary separation, i.e., $\propto (1+q)^{-2/3}P_{\rm orb}^{-4/3}$. Assuming the flux is proportional to the mass transfer rate, we can express $T_{\rm reb}^{-1} \propto (1+q)^{-2/3}P_{\rm orb}^{-4/3}$.

3.3 result

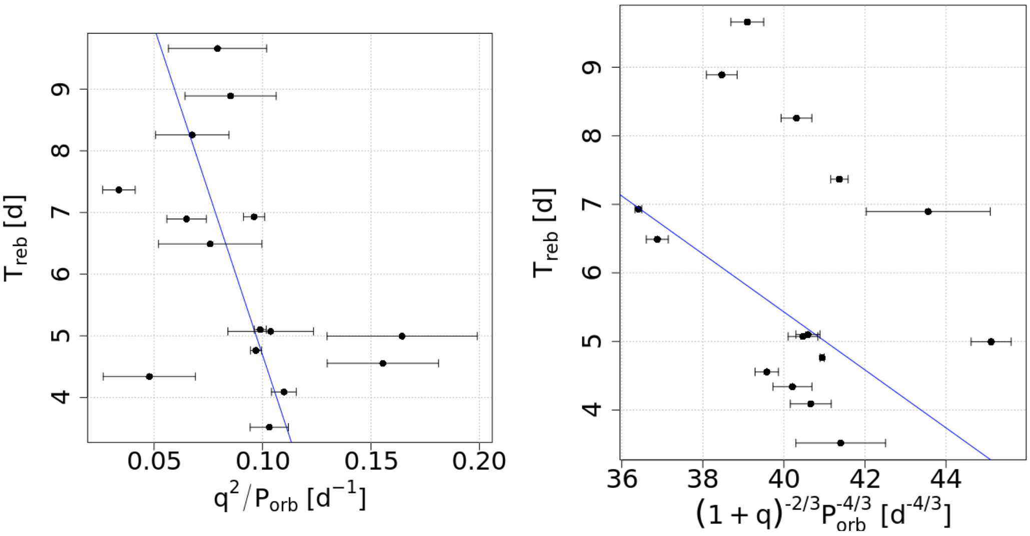

Figure 4: Correlation between the representative binary parameters (left; MR and right; EMT) and $T_{\rm reb}$. The solid line represents error-weighted linear regression. Both of the models show a negative correlation.

According to Sec.3.2.1 and 3.2.2, both of the models have parameters that relate to $T_{\rm reb}$. Calculating the correlation coefficients for each variable yields the results shown in Fig.4. The p-values of the MR and EMT models are 0.0145 and 0.000517, respectively. These results indicate that considering $T_{\rm reb}$ in this study did not reveal any significant differences between the two models.

4. Summary

We observed the WZ Sge-type dwarf nova GOTO0650 and classified it as type E+B. It exhibited a long period of ~100 days and numerous rebrightening events (11 rebrightenings). However, when viewed in terms of $T_{\rm reb}$ variable, it was not significantly different from other type B objects. Comparing the MR and EMT models of rebrightening outbursts from the viewpoint of $T_{\rm reb}$ revealed no significant difference.

5. Acknowledgments

This work makes use of observations from the Las Cumbres Observatory global telescope network. Based on observations obtained with the Samuel Oschin Telescope 48-inch and the 60-inch Telescope at the Palomar Observatory as part of the Zwicky Transient Facility project. ZTF is supported by the National Science Foundation under Grant No. AST-2034437 and a collaboration including Caltech, IPAC, the Weizmann Institute for Science, the Oskar Klein Center at Stockholm University, the University of Maryland, Deutsches Elektronen-Synchrotron and Humboldt University, the TANGO Consortium of Taiwan, the University of Wisconsin at Milwaukee, Trinity College Dublin, Lawrence Livermore National Laboratories, and IN2P3, France. Operations are conducted by COO, IPAC, and UW. We acknowledge with thanks the variable star observations from the AAVSO International Database contributed by observers worldwide and used in this research. We acknowledge with thanks the variable star observations from VSOLJ (Variable Star Observers League of Japan) contributed by observers and used in this research.

References

[1] Osaki, 1989, Publications of the Astronomical Society of Japan, Volume 41, Issue 5, pp. 1005-1033, 29 pp.

[2] Osaki, 1996, Publications of the Astronomical Society of the Pacific, v.108, p.39

[3] Whitehurst, 1988, Monthly Notices of the Royal Astronomical Society, Vol. 232, 35-51

[4] Hirose and Osaki, 1990, Publications of the Astronomical Society of Japan, Volume 42, Issue 1, pp. 135-163, 29 pp.

[5] Kato, 2015, Publications of the Astronomical Society of Japan, Volume 67, Issue 6, id.108 42 pp.

[6] Kato et al., 1998, Wild Stars In The Old West: Proceedings of the 13th North American Workshop on Cataclysmic Variables and Related Objects. ASP Conference Series, Vol. 137, ed. S. Howell, E. Kuulkers, and C. Woodward, p.9

[7] Osaki, 2001, Astrophysical Ages and Times Scales, ASP Conference Series Vol. 245. Edited by Ted von Hippel, Chris Simpson, and Nadine Manset. San Francisco: Astronomical Society of the Pacific, ISBN: 1-58381-083-8., p.57

[8] Hameury et al., 2000, Astronomy and Astrophysics, v.353, p.244-252

[9] Osaki et al., 1997, Publications of the Astronomical Society of Japan, v.49, p.L19-L23.

[10] killestein et al., 2025, Astronomy & Astrophysics, Volume 699, id.A8, 14 pp.

[11] Dyer et al., 2018, Proceedings of the SPIE, Volume 10704, id. 107040C 14 pp.

[12] Dyer et al., 2024, Proceedings of the SPIE, Volume 13094, id. 130941X 8 pp.

[13] Steeghs et al., 2022, Monthly Notices of the Royal Astronomical Society, Volume 511, Issue 2, pp.2405-2422

[14] Castro-segura et al., 2025, Monthly Notices of the Royal Astronomical Society: Letters, Volume 541, Issue 1, pp. L28-L34, 7 pp.

[15] Killestein et al., 2025, The Astronomer's Telegram, No. 16842

[16] Kato et al., 2004, Publications of the Astronomical Society of Japan, Volume 56, Issue sp1, p.S1-S54

[17] Brown, T. M. et al., 2013, Publications of the Astronomical Society of the Pacific, Volume 125, Issue 931, pp. 1031

[18] Masci et al., 2019, Publications of the Astronomical Society of the Pacific, Volume 131, Issue 995, pp. 018003

[19] Knigge, 2006, Monthly Notices of the Royal Astronomical Society, Volume 373, Issue 2, pp. 484-502.

[20] Patterson et al., 1998, The Publications of the Astronomical Society of the Pacific, Volume 110, Issue 753, pp. 1290-1303.

[21] Kato, 2017, Publications of the Astronomical Society of Japan, Volume 69, Issue 5, id.75

[22] Knigge et al., 2011, The Astrophysical Journal Supplement, Volume 194, Issue 2, article id. 28, 48 pp.

[23] Kato, 2009 , Publications of the Astronomical Society of Japan, Volume 61, Issue sp2, p.S395-S616

[24] Pala et al.,2022 , Monthly Notices of the Royal Astronomical Society, Volume 510, Issue 4, pp.6110-6132

[25] Lubow, 1991, Astrophysical Journal v.381, p.259

[26] Lin and Papaloizou, 1979, Monthly Notices of the Royal Astronomical Society, Vol. 186, 799-812

[27] Warner,B, 2015, Memorie della Societa Astronomica Italiana, v.86, p.129