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On the M_V–Inclination Relationship for Nova-like Variables

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Abstract

Using a sample of Nova-like stars from the Ritter & Kolb catalog, we examine the relationship between their *Gaia*-determined absolute magnitude and the inclination of the binary system. Webbink et al. derived a relationship between these two variables that provides a good fit and allows differentiation between $\dot{M}$ (and possibly $M_{\rm WD}$) as a function of inclination. We show that the spread in M_V, at a given i, is dominated by the mass-transfer rate with only a small dependence on the white dwarf mass. The validated relation shows that present-day theoretical population studies of cataclysmic variables, as well as model fits to observational data, yield mass-transfer rates and white dwarf masses consistent with the *Gaia*-derived M_V for the nova-like stars.

Key words: accretion, accretion disks – binaries: general – novae, cataclysmic variables – stars: dwarf novae

1. Introduction

There have been a number of previous works that attempted to discern the relationship between the absolute magnitude (M_V) of an accretion-disk-bearing binary star (i.e., a cataclysmic variable) and its system inclination. In principle, such a relationship is easy to imagine since seeing the accretion disk face-on will make the binary system substantially brighter than seeing only the thin edge of cooler material. From both first principles (Mayo et al. 1980; Paczynski & Schwarzenberg-Czerny 1980) and observational results mixed with theory (Warner 1986; Webbink et al. 1987), astronomers have produced a number of empirical relationships for M_V versus i as an aid in the quest to understand the disk structure and distances to such binaries. More recently, general values and equations based on the above accepted paradigms pervade the literature and are casually used and accepted as correct for individual or classes of stars (e.g., Warner 2003, Patterson 2011; Ramsay et al. 2017).

The original relationships mentioned above were developed for specific cases: U Gem, UX UMa-like disks, recurrent novae, and nova remnants. Most of these types of cataclysmic variables generally have one thing in common—their accretion disk is believed to be (or was modeled as) optically thick, with the disk dominating the light output in the visible part of the spectrum. However, these past studies used a mixture of system types, orbital periods, and techniques to formulate their relationships.

In this paper, we revisit the connection between a bright disk system's absolute magnitude and its inclination. We use a model-independent approach based on a set of nova-like stars and new results from *Gaia* data release two (DR2). We assume that in our stars M_V is dominated by the light from the optically thick disk and that, for a constrained range in orbital period, their system properties are similar such that the disk inclination will dominate M_V, with white dwarf mass, q, and mass-transfer rate being second-order effects. There is, of course, much observational evidence that shows that disks of nova-like systems are optically thick (e.g., Baptista et al. 1995a, 1995b; Bisol et al. 2012). Our assumptions are well-founded based on theoretical results (e.g., Kolb & Baraffe 2000; Howell et al. 2001) and the literature reviewed in retrospect.

We discuss our sample in the next section, review some of the original relationships, and highlight their features in Section 3. Finally, in the final section we summarize our results, and—spoiler—we find that the old, venerable relationships work pretty well.

2. The Nova-like Sample

We selected our sample of nova-like stars from the 2014 version of the Kolb & Ritter CV Catalog.[3] We selected all stars listed as "NL" within the orbital period range of 3–6 hr. This search gave us 87 stars, of which 25 had inclination and other pertinent system information that made up our sample list. While we are aware that this sample is not complete, it is sufficient to demonstrate the goals of this paper. Since the inclination, i, is the parameter of interest here, we have checked its value for each of the objects in the sample. In particular, we made sure that each inclination value that we adopted (either as reported in the Ritter & Kolb catalog or by some other source) was derived by careful light-curve modeling (through multiple sources) and/or spectroscopic/radial velocity studies. In the few cases where the error was not listed in the published work, we estimated it ourselves using the published information (e.g., the either stellar component mass uncertainties or the presented graphic solution). Four objects have only a range constraint for their inclination.

For these 25 stars, we queried *Gaia* DR2 in the Heidelberg ARI's *Gaia* mirror site (http://gaia.ari.uni-heidelberg.de/) first to get the GDR2 ID numbers of each source and then the corresponding best distance as estimated by Bailer-Jones et al. (2018). The distance information was derived by the *Gaia* team (Gaia Collaboration et al. 2018; Luri et al. 2018) and includes their error estimates (min/max distance), manifested in our M_V values as uncertainties. The *Gaia* team performed extensive tests of their distance determinations throughout the sky in terms of the correctness and uncertainties (See Clementini et al. 2018; Luri et al. 2018). No ARI distance was available for SW Sex, thus it was removed from our sample. Table 1 lists our final sample of 24 stars. OY Ara shows a larger than usual *Gaia*

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[3] https://heasarc.gsfc.nasa.gov/W3Browse/all/rittercv.html

Table 1
Sample of NL with Known Orbital Inclination Extracted from the Ritter & Kolb Catalog and Cross-correlated with the *Gaia* DR2 and the *Gaia* TAP Service of the Astronomisches Rechen Institut (ARI; Bailer-Jones et al. 2018)

Name	*Gaia* ID	d (pc)	$d_{\mathrm{min\,/\,max}}$ (pc)	M_V (mag)	V (mag)	$i \pm \sigma_i$ (°)	P_{orb} (hr)	i ref
WX Ari	22272497806324480	664	605/735	6.2	15.3	72–82[a]	3.344	Rodríguez-Gil et al. (2000)
RW Tri	130692247044752784	312	308/317	5.0	12.5	70.5 ± 2.5	5.565	Smak (1995)
J0107+4845	401879681868136704	748	714/786	5.5	14.9	81.4 ± 0.1	4.646	Khruzina et al. (2013)
DW UMa	855119196836523008	577	565/590	4.8	13.6	82 ± 4	3.279	Araujo-Betancor et al. (2003)
J0809+3814	908714959852556672	1222	1153/1300	5.2	15.6	65 ± 5	3.217	Linnell et al. (2007a)
V482 Cam	1108037726271701120	547	535/560	7.0	15.7	85 ± 4	3.207	Rodriguez-Gil et al. (2004)
LX Ser	1209876314302933504	486	476/496	5.7	14.1	80 ± 3	3.802	Magnuson (1984)
UX UMa	1559987685901122560	295	293/297	5.2	12.5	73 ± 1.8	4.72	Smak (1994)
CM Del	1815021160316471808	403	398/408	5.4	13.4	73 ± 47	3.888	R&K[b]
V425 Cas	1996248233085177600	886	862/911	4.8	14.5	25 ± 9	3.59	R&K[b]
V1776 Cyg	2083145484587589632	1057	993/1130	6.1	16.2	75^{+2}_{-1}	3.954	Garnavich et al. (1990)
MV Lyr	2106069275529926400	493	481/505	3.3	11.8	7 ± 1	3.176	Linnell et al. (2005)
VY Scl	2329317895999827968	630	607/654	3.1	12.1	15 ± 10	5.575	Schmidtobreick et al. (2018)
VZ Scl	2337436792938619392	552	534/571	6.9	15.6	76–90[a]	3.471	Odonoghue et al. (1987)
0220+0603	2517357336654841856	717	656/790	7.0	16.3	79.1–79.7	3.581	Rodriguez-Gil et al. (2015)
UU Aqr	2675351827511262720	254	249/259	6.3	13.3	78 ± 2	3.931	Baptista et al. (1996)
KR Aur	3436435910858051072	451	377/563	4.4	12.7	20–40[a]	3.907	Hutchings et al. (1983)
RW Sex	3769067109159365120	235	230/240	3.0	9.9	34 ± 2	5.882	Vande Putte et al. (2003)
V1315 Aql	4313192491505026560	443	437/449	6.1	14.3	82.1 ± 3.6	3.353	Dhillon et al. (1991)
V380 Oph	4474002634076551680	667	635/702	5.2	14.3	42 ± 13	3.699	R&K[b]
RR Pic	5477422099543151616	504	496/512	3.5	12.0	60–80[a]	3.481	Ribeiro & Diaz (2006)
IX Vel	5515820034889609216	90	90/91	4.2	9.0	57 ± 2	4.654	Linnell et al. (2007b)
V347 Pup	5553468275089335296	293	292/295	6.1	13.4	84.0 ± 2.3	5.566	Thoroughgood et al. (2005)
OY Ara	5931112341266391040	3175	2064/5573	6.2	18.7	74.4 ± 1.3	3.731	Zhao & McClintock (1997)

Notes.
[a] These stars only have inclination ranges.
[b] Inclination values (and error) are from the Ritter & Kolb catalog, in reference to the unpublished Shafter (1983) PhD thesis.

distance uncertainty due to the object's faint apparent magnitude.

Using the catalog high-state V magnitude for each NL, we calculated its M_V. We note that most of our objects have $E(B-V)$ consistent with zero (see the literature discussed below), thus we ignore reddening in the distance determinations. Table 1 lists the distance information calculated by the *Gaia* team, including the most likely and limiting values, and our calculated absolute magnitude values. We find no correlation of M_V with orbital period or distance as expected, but given the generally similar distances (200–800 pc) of the stars in the sample, the brighter absolute magnitude stars are also generally brighter in V magnitude as well.

According to theory (e.g., Kolb & Baraffe 2000; Howell et al. 2001; Kolomeni et al. 2016), these stars should have mass-transfer rates between 10^{-8} and $10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$, providing them with a bright, steady optically thick accretion disk yielding ∼100% of the optical light from the system.

3. Absolute Magnitude versus Inclination

Using the information in Table 1, we plot the actual M_V values versus the cosine of the system inclination (Figure 1). Note that RR Pic and OY Ara are known historical novae: Nova Pic 1925 and Nova Ara 1910, respectively. While it might be more correct to discard these two objects altogether from our sample, we preferred to keep them in since a ≃100 year old nova might be old enough to be considered a quiescent cataclysmic variable (NL). Additionally, recent observations by Sahman et al. (2018) have suggested that V1315 Aql might also have been a nova in the past. In Figure 1, we did not plot CM Del because its inclination uncertainty is so large

We note a cosine-like dependence on the system brightness versus i. This is not surprising, and in fact was expected based on our assumption that the luminosity of the disk dominates the light in the optical part of the spectrum. We also see that for a given cos i value, there is a spread of about 2.5 mag in M_V.

Two of the best known and well used M_V–inclination relationships, progenitors of present-day relations and usage, are those of Warner (1986) and Webbink et al. (1987). Warner made use of new absolute magnitude determinations of novae at maximum based on the shell expansion parallax method. He then determined the inclination of each nova remnant by measuring and fitting emission-line equivalent widths, which he then used as a proxy for viewing angle. Combining these two measured values, available for 13 systems, Warner constructed a plot of M_V versus cos i. While a straight line would have fit his data fairly well, the goal was to see if these data matched the expected M_V versus cos i relation predicted by theory. Paczynski & Schwarzenberg-Czerny (1980) had developed such a relation based on a disk model they produced for the dwarf nova U Gem during outburst. Warner used their equation (16), adopting the recommended limb-darkening value of $\mu = 0.6$ to attempt a match for the distribution of 13 nova remnants in the M_V versus cos i plane. The Paczynski and Schwarzenberg-Czerny relationship provided only a delta

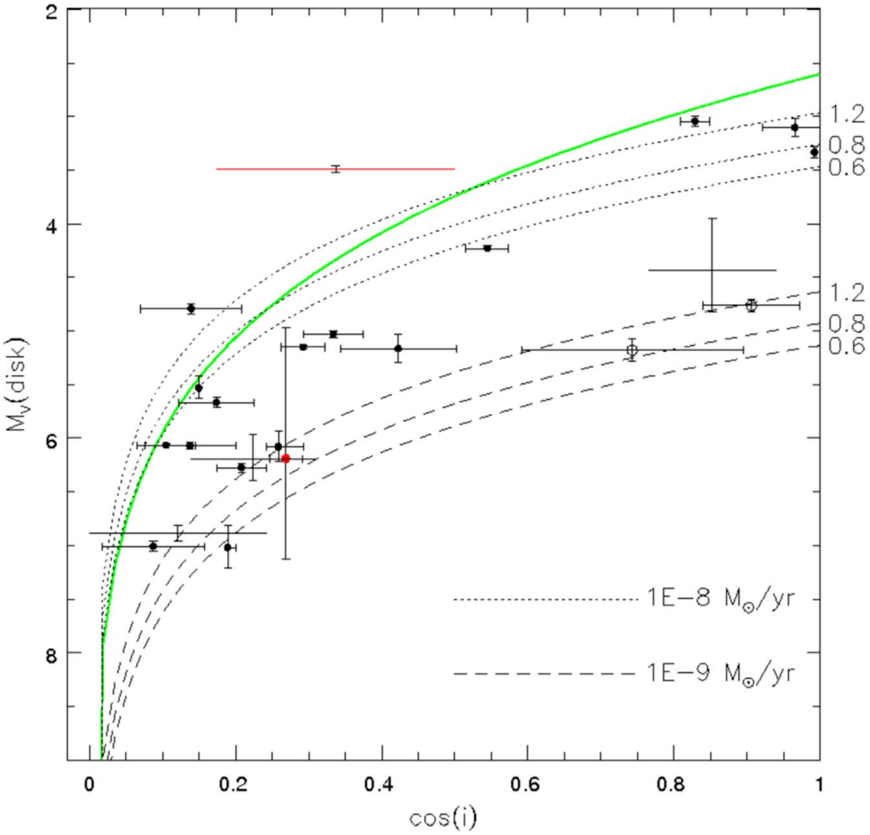

Figure 1. M_V (as calculated from *Gaia* Release 2 distances) vs. cos(i) for our Ritter & Kolb NL sample whose system parameters are listed in Table 1. The black filled circles are systems with published inclination and uncertainty values that we could verify; the empty circles are for the systems whose inclination and error information come from the Ritter & Kolb catalog quoting the unpublished Shafter (1983) PhD thesis; the horizontal bars are for those objects with just an inclination constraint in the literature and not a precise determination. The red denotes the two old novae RR Pic and OY Ara. The dotted and dashed lines represent the expected absolute magnitude for mass-transfer rates of 10^{-8} and 10^{-9} $M_\odot$ yr^{-1}, respectively, per Webbink et al.'s formula given in the text. The number on the side of each theoretical line indicates the adopted WD mass in solar units. The solid green line is the Warner (1986) relation derived using the Paczynski & Schwarzenberg-Czerny (1980) formulation.

magnitude variation for the geometric aspect effect,

$$\Delta M_V(i) = -2.5\log[(1 + 3/2\cos i)\cos i],$$

making the relationship fully geometric in nature. This expression provides the expected change in M_V when the disk is tilted above or below an inclination of 56°.7 ($\Delta M_V = 0$), setting $\Delta M_V = 4.4$ for inclinations ⩾89°. We present (green line) in Figure 1 Warner's version of the Schwarzenberg-Czerny relation. Warner's nova remnants spanned ~10–100 years after outburst, so the accretion disks in the systems represent a heterogeneous mixture of M_V values. Thus, while this fit follows the general trend in Figure 1, its tie to physical disk parameters is uncertain.

Soon after Warner's publication, Webbink et al. (1987) made a detailed study of recurrent novae and provided an independent view of the relationship between the observed M_V and system inclination. Starting with the basic equations for the luminosity and effective temperature distribution of the standard model accretion disk (c.f., Shakura & Sunyaev 1973), Webbink et al. convolved the disk luminosity output with a standard V filter and included a geometric inclination dependence to yield

$$M_V(\mathrm{obs}) = -9.48 - 5/3\log(M_{\mathrm{WD}}\dot{M}) - 5/2\log(2\cos i),$$

where M_{WD} = the mass of the white dwarf in solar masses and $\dot{M}$ is the mass accretion rate of the system in $M_\odot$ yr^{-1}. This relationship provides the expected observed M_V value based on the physical parameters of the system.

Unlike Warner's empirical relationship, the Webbink et al. equation contains a dependence of the disk luminosity on white dwarf mass and mass accretion rate. Figure 1 shows the Webbink et al. results for the cases of mass accretion rates of 10^{-8} (dotted line) and 10^{-9} $M_\odot$ yr^{-1} (dashed line), the limiting values expected for these stars, with white dwarf masses of 0.6, 0.8, 1.2 $M_\odot$.

The two M_V–cos i relations discussed above provide fairly good fits to the data, revealing the general trend and suggesting that the mass accretion rate is the dominant cause of the spread at any given inclination. But do the literature findings agree?

Let us examine a few examples, paying particular attention to the mass accretion rate and the white dwarf mass. From the literature we find that the stars MV Lyr (Godon et al. 2017), RW Sex (Hernandez 2017), VY Scl (Hamilton & Sion 2008), RR Pic[4] (Sion et al. 2017), and DW UMa (Smak 2017) all are shown to have high mass accretion rates, near 10^{-8} $M_\odot$ yr^{-1}, while the stars UU Aqr (Dobrotka et al. 2012) and V380 Oph (Zellem et al. 2009) show rates near 10^{-9} $M_\odot$ yr^{-1}, the lowest expected values for these types of stars. IX Vel

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[4] Note that RR Pic, while listed in the Kolb & Ritter CV Catalog as an NL, is an old nova. Such stars have been shown to maintain increased mass accretion rates long after their eruptions, which are possibly the reasons for their higher absolute brightness.

(Linnell et al. 2007b) and UX UMa (Linnell et al. 2008) have modeled mass accretion rates that are intermediate to these two groups.

We note that a change in disk radius (r) between equivalent systems could also cause a change in disk luminosity ($L \propto r^2$). Using the standard relation between the outer disk radius and q (Lubow & Shu 1975), we note that even a change in mass ratio from 0.35 (e.g., V425 Cas) to 0.74 (e.g., RW Sex) makes at most a change in r of $\sim$1.4, providing $<$0.5 mag of luminosity change for a uniformly bright disk. Real disks are brighter at smaller r values, so in reality, any minimal areal reduction produces only a small change in disk brightness. Additionally, we see no discernible effects in Figure 1 based on mass ratio or orbital period in terms of M_V value.

We also note that RR Pic, RW Sex, and DW UMa contain high-mass white dwarfs, 0.85–0.95 $M_\odot$, placing them at the brightest level for their inclination. Thus, it appears that WD mass does produce a second-order, possibly discernible effect. The Webbink et al. model fits shown in Figure 1 seem consistent with the literature values for $\dot{M}$ and $M_{\rm WD}$.

4. Summary

We have used a sample of nova-like systems with orbital periods of 3–6 hr and containing accretion disks that dominate the light in the visible part of the spectrum. Taking the new *Gaia* DR2 parallax results, we determined the absolute magnitudes for these stars, and with system inclinations taken from the Kolb & Ritter CV catalog and current references, produced the relationship between M_V and i.

Two previous M_V–i relationships, based on disk models, initially applied to nova remnants, and still in use today, were examined and proved to be fairly representative of the data.

Webbink et al. (1987) derived a relationship between these two variables that provides a good fit to the observations and allows differentiation between $\dot{M}$ values for a given i. We show that the spread in M_V, for a given inclination, is indeed dominated by the mass-transfer rate (i.e., the disk luminosity being proportional to T^4; see Equation (5.20), Frank et al. 1992) with a small, but perhaps measurable dependence on the white dwarf mass.

Additionally, we confirm that modern theoretical population studies of cataclysmic variables, as well as model fits to observational data for individual systems, as discussed in various literature articles, yield derived mass-transfer rates that are consistent with the true M_V for nova-like stars.

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References

Araujo-Betancor, S., Knigge, C., Long, K. S., et al. 2003, ApJ, 583, 437
Bailer-Jones, J., Rybizki, M., Fouesneau, G., et al. 2018, arXiv:1804.10121
Baptista, R., Horne, K., Hilditch, R. W., et al. 1995a, ApJ, 448, 395
Baptista, R., Steiner, J. E., & Cieslinski, D. 1995b, ApJ, 433, 332
Baptista, R., Steiner, J. E., & Horne, K. 1996, MNRAS, 282, 99
Bisol, A., Godon, P., & Sion, E. 2012, PASP, 124, 158
Clementini, G., Garofalo, A., Muranena, T., & Ripepi, V. 2018, arXiv:1804.09575
Dhillon, V. S., Marsh, T. R., Jones, D. H. P., et al. 1991, MNRAS, 252, 342
Dobrotka, A., Mineshige, S., & Casares, J. 2012, MNRAS, 420, 2467
Frank, J., King, A., & Raine, D. 1992, Accretion Power in Astrophysics (Cambridge: Cambridge Univ. Press)
Gaia Collaboration et al. 2018, arXiv:1804.09365
Garnavich, P. M., Szkody, P., Mateo, M., et al. 1990, ApJ, 365, 696
Godon, P., Sion, E. M., Balman, S., & Blair, W. P. 2017, ApJ, 846, 52
Hamilton, R., & Sion, E. 2008, PASP, 120, 165
Hernandez, D. 2017, MNRAS, 470, 1960
Howell, S. B., Rappaport, S., & Nelson, L. 2001, ApJ, 550, 897
Hutchings, J. B., Link, R., & Crampton, D. 1983, PASP, 95, 264
Khruzina, T., Dimitrov, D., & Kjurkchieva, D. 2013, A&A, 511, A125
Kolb, U., & Baraffe, I. 2000, NewAR, 44, 99
Kolomeni, B., Nelson, L., Rappaport, S., et al. 2016, ApJ, 833, 83
Linnell, A. P., Godon, P., Hubeny, I., Sion, E. M., & Szkody, P. 2007b, ApJ, 662, 1204
Linnell, A. P., Godon, P., Hubeny, I., Sion, E. M., & Szkody, P. 2008, ApJ, 688, 568
Linnell, A. P., Hoard, D. W., Szkody, P., et al. 2007a, ApJ, 654, 1036
Linnell, A. P., Szkody, P., Gänsicke, B., et al. 2005, ApJ, 624, 923
Lubow, S. H., & Shu, F. H. 1975, ApJ, 198, 383
Luri, X., Brown, A. G. A., Sarro, L. M., et al. 2018, arXiv:1804.09376
Magnuson, J. A. 1984, PhD thesis, Dartmouth College
Mayo, S. K., Wickramasinge, D. T., & Whelan, J. A. J. 1980, MNRAS, 193, 793
Odonoghue, D., Fairall, A. P., & Warner, B. 1987, MNRAS, 225, 43
Paczynski, B., & Schwarzenberg-Czerny, A. 1980, AcA, 30, 127
Patterson, J. 2011, MNRAS, 411, 2695
Ramsay, G., Schreiber, M. R., Gänsicke, B. T., & Wheatley, P. J. 2017, A&A, 604, 107
Ribeiro, F. M. A. P., & Diaz, M. P. 2006, PASP, 118, 84
Rodríguez-Gil, P., Casares, J., Dhillon, V. S., & Martínez-Pais, I. G. 2000, A&A, 355, 181
Rodriguez-Gil, P., Gänsicke, B. T., Barwig, H., Hagen, H.-J., & Engels, D. 2004, A&A, 424, 647
Rodriguez-Gil, P., Shahbaz, T., Marsh, T. R., et al. 2015, MNRAS, 452, 146
Sahman, V. S., Dhillon, V. S., Littlefair, S. P., & Hallinan, G. 2018, MNRAS, 477, 4483
Schmidtobreick, L., Mason, E., Howell, S. B., et al. 2018, A&A, 617, A16
Shafter, A. W. 1983, PhD thesis, UCLA
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Sion, E., Godon, P., & Jones, L. 2017, AJ, 153, 109
Smak, J. 1994, AcA, 44, 59
Smak, J. 1995, AcA, 45, 259
Smak, J. 2017, AcA, 67, 273
Thoroughgood, T. D., Dhillon, V. S., Steeghs, D., et al. 2005, MNRAS, 357, 881
Vande Putte, D., Smith, R. C., Hawkins, N. A., & Martin, J. S. 2003, MNRAS, 341, 151
Warner, B. 1986, MNRAS, 222, 11
Warner, B. 2003, Cataclysmic Variables (Cambridge: Cambridge Univ. Press)
Webbink, R. F., Livio, M., Truran, J. W., & Orio, M. 1987, ApJ, 314, 653
Zellem, R., Hollon, N., Ballouz, R.-L., et al. 2009, PASP, 121, 942
Zhao, P., & McClintock, J. E. 1997, ApJ, 483, 899