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 $M$ (and possibly $M_{\text{WD}}$) 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.

2. The Nova-like Sample

We selected our sample of nova-like stars from the 2014 version of the Kolb & Ritter CV Catalog. 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
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; Kolomenei et al. 2016), these stars should have mass-transfer rates between $10^{-8}$ and $10^{-9} M_\odot$ yr$^{-1}$, providing them with a bright, steady optically thick accretion disk yielding $\sim$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 $\sim$100 year old nova might be old enough to be considered a quiescent cataclysmatic 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.

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 their 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 (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 (Zelllem et al. 2009) show rates near $10^{-9} M_\odot$ yr$^{-1}$, the lowest expected values for these types of stars. IX Vel

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.

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^\circ$7 ($\Delta M_V = 0$), setting $\Delta M_V = 4.4$ for inclinations $\geq 89^\circ$. 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

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

where $M_{\text{WD}}$ = 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 $M_\odot$.

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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, $0.85\pm0.95 M_{\odot}$, 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 $M$ and $M_{WD}$.

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 $M$ 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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