

A *Hubble Space Telescope* Survey for Novae in M87. II. Snuffing out the Maximum Magnitude - Rate of Decline Relation for Novae as a Non-Standard Candle, and a Prediction of the Existence of Ultrafast Novae¹

Michael M. Shara^{2,3}, Trisha Doyle^{2,4}, Tod R. Lauer⁵, David Zurek², Edward A. Baltz⁶, Attay Kovetz⁷, Juan P. Madrid⁸, Joanna Mikołajewska⁹, J.D. Neill¹⁰, Dina Prialnik¹¹, D. L. Welch¹², and Ofer Yaron¹³

ABSTRACT

The extensive grid of numerical simulations of nova eruptions of Yaron et al. (2005) first predicted that some classical novae might deviate significantly from

¹Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555.

²Department of Astrophysics, American Museum of Natural History, Central Park West and 79th Street, New York, NY 10024-5192, USA

³Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom

⁴Department of Physics and Space Sciences, Florida Institute of Technology, Melbourne, FL 32901, USA

⁵National Optical Astronomy Observatory, P.O. Box 26732, Tucson, AZ 85726, USA

⁶KIPAC, SLAC, 2575 Sand Hill Road, M/S 29, Menlo Park, CA 94025, USA

⁷School of Physics and Astronomy, Faculty of Exact Sciences, Tel-Aviv University, Tel Aviv, Israel

⁸CSIRO, Astronomy and Space Science, P.O. Box 76, Epping, NSW 1710, Australia

⁹N. Copernicus Astronomical Center, Polish Academy of Sciences, Bartycka 18, PL 00-716 Warsaw, Poland

¹⁰California Institute of Technology, 1200 East California Boulevard, MC 278-17, Pasadena CA 91125, USA

¹¹Department of Geosciences, Tel Aviv University, Ramat Aviv, Tel Aviv 69978, Israel

¹²Department of Physics & Astronomy, McMaster University, Hamilton, L8S 4M1, Ontario, Canada

¹³Department of Particle Physics and Astrophysics, Weizmann Institute of Science, 76100 Rehovot, Israel

the Maximum Magnitude - Rate of Decline (MMRD) relation, which purports to characterise novae as standard candles. Kasliwal et al. (2011) have announced the observational detection of an apparently new class of faint, fast classical novae in the Andromeda galaxy. These objects deviate strongly from the MMRD relationship, exactly as predicted by Yaron et al. (2005). Shara et al. (2016) recently reported the first detections of faint, fast novae in M87. These previously overlooked objects are as common in the giant elliptical galaxy M87 as they are in the giant spiral M31; they comprise about 40% of all classical nova eruptions and greatly increase the observational scatter in the MMRD relation. We use the extensive grid of nova simulations of Yaron et al. (2005) to identify the underlying causes of the existence of faint, fast novae. These are systems which have accreted, and can thus eject, only very low mass envelopes, of order $10^{-7} - 10^{-8} M_{\odot}$, on massive white dwarfs. Such binaries include, but are not limited to, the recurrent novae. These same models predict the existence of ultrafast novae which display decline times t_2 as short as five hours. We outline a strategy for their future detection.

Subject headings: M87, novae, cataclysmic variables

1. Introduction and Motivation

Most astronomers connect Edwin Hubble with the year 1929 because of his momentous paper “A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae” (Hubble 1929), which initiated the study of modern cosmology. In the same month, however, Hubble also published “A Spiral Nebula as a Stellar System, Messier 31” (Hubble 1929), in which he announced the resolution of the outer spiral arms of that galaxy into swarms of faint stars; the discovery of Cepheids and long-period variables; and 63 novae. The study of extragalactic stellar populations thus began at the same time as cosmology, and classical novae have played a significant role in populations studies ever since.

Novae are all binaries in which a white dwarf (WD) accretes matter from a hydrogen-rich brown dwarf, red dwarf or red giant companion; or helium from a white dwarf companion. When sufficient mass is accumulated that degenerate electron pressure at the base of the accreted envelope exceeds a critical value, a thermonuclear runaway (TNR) occurs, which ejects most of the envelope and brightens the WD to its Eddington luminosity or even brighter (Shara 1981a). Novae near maximum light range in luminosity from $M = -6$ to -10 (Warner 1995). In contrast, the bright end of the planetary nebula (PN) luminosity function only reaches $M(5007) = -4.5$ (Ciardullo et al. 1989); red giant branch (RG) stars typically

reach $M = -3$ (Baade 1944; Sandage 1971); and RR Lyrae stars achieve $M_V = 0.6$ (Christy 1966). Novae can therefore be detected much more easily in a given galaxy or cluster, and can be observed to significantly greater distances in the field than PN, RG or RR Lyrae stars. The transient nature of novae and their $H\alpha$ brightness help eliminate contamination due to background emission line objects or unresolved compact galaxies.

Zwicky (1936) was the first to announce that novae appeared to behave as standard candles, with light curves that could be calibrated to yield the distances to galaxies. Zwicky’s first formulations of the MMRD correlation were improved upon by Mclaughlin (1945) and Arp (1956). The physics of the apparently tight correlation between nova absolute magnitude at maximum light and their rates of brightness decline was explained by Shara (1981a) and Livio (1992). The key prediction of those investigations is that, all other things being equal, the mass of the white dwarf in a nova binary is the dominant parameter controlling the behaviours of nova explosions.

The essential physics underlying this prediction is as follows. The degenerate equation of state of matter in a WD determines that as the mass of a WD increases, its radius decreases (Chandrasekhar 1931, 1935). Thus the acceleration of gravity at a WD’s surface increases sharply as its mass increases. A strongly increasing gravitational potential, with increasing WD mass, means that much less hydrogen can be accreted onto the WD before a TNR occurs (Shara 1981a). Lower mass envelopes can be ejected faster than those of higher mass, so novae occurring on massive WDs will exhaust their thermonuclear-powered envelopes, and decline in brightness faster, than those on low mass WDs. If WD mass was the *only* free parameter then novae would be luminous, well-understood standard candles displaying negligible scatter.

Of course, all other things are *not* equal, and novae are decidedly *not* a phenomenon governed by just one free parameter (Starrfield et al. 1975; Shara et al. 1980). While it is widely recognized that WD mass is a critical factor affecting nova explosions, as noted above, it is now understood there are at least four other important factors that determine the properties of a nova outburst. These are the accretion rate onto the WD and the resulting envelope mass (Prialnik et al. 1982); the WD luminosity (Prialnik & Kovetz 1995; Yaron et al. 2005); its chemical composition (He, CO or ONe), and the chemical composition of the accreted matter (H-rich or He) (Faulkner et al. 1972; Kovetz & Prialnik 1985; Starrfield et al. 1986). Just the WD mass, accretion rate/envelope mass and luminosity can and do produce a rich variety of nova eruptions (Prialnik & Kovetz 1995; Yaron et al. 2005) and scatter about the so-called MMRD relation. Referring to their nova models, Prialnik & Kovetz (1995) stated that “Correlations are obtained between the peak luminosity and time of decline...It is shown that these correlations cannot be tight...The implication is that novae cannot be considered

accurate distance indicators”. Do observations bear out this prediction?

Early attempts to measure distances of nearby galaxies, and even to deduce the Hubble constant via novae, had a reasonably good track record. Capaccioli et al. (1989) used Cohen (1985)’s calibration of Galactic novae to obtain a distance modulus for M31 of 24.27 ± 0.2 , in good agreement with $(m-M) = 24.46 \pm 0.10$ recently obtained by de Grijs & Bono (2014). Capaccioli et al. (1990) found a distance to the LMC of $(m-M) = 18.7 \pm 0.2$, in equally good agreement with the modern value of 18.48 ± 0.10 (Inno et al. 2016). della Valle & Livio (1995) used the M31 and LMC MMRDs to obtain a Virgo cluster distance of $18.6+3.3$ Mpc, which exceeds by 13% the modern distance of 16.4 ± 0.5 Mpc (Bird et al. 2010). Finally, using a sample of just seven novae, a value of the Hubble constant of 70 ± 13 km/s/Mpc was obtained by van den Bergh (1992). della Valle & Livio (1995) summarised these studies, stating that novae can be used judiciously, when geometric and nebular parallaxes are not available, with roughly 30% errors in distance measurements, to non-recurrent Galactic novae. In the modern era of precision cosmology novae are not competitive with much more precise values of the Hubble constant obtained via type Ia supernovae (e.g. Riess et al. (2011)), but 25 years ago the MMRD seemed to be a much better distance indicators than the pessimistic assessment of Prialnik & Kovetz (1995) then indicated.

Doubts about the MMRD relation were first raised by Ferrarese et al. (2003), who noted that:

“We examine the maximum magnitude versus rate of decline (MMRD) relation for novae in M49, finding only marginal agreement with the Galactic and M31 MMRD relations.” Up to six of the nine novae detected with the Hubble Space Telescope (HST) in this study appear to be anomalously faint for their fast rates of decline, but conclusive maxima were only seen for three of the nine novae.

A similar conclusion was reached the following year by Hearnshaw et al. (2004) who, on the basis of 4 well-observed fast novae in the LMC concluded:

“The weighted mean distance modulus to the LMC based on these novae is 18.89 ± 0.16 . This differs significantly from the distance modulus adopted by della Valle & Livio of 18.50...The evidence based on these novae suggests that... some novae in the LMC, including these four, are significantly underluminous at maximum light compared with those in M31, by about 0.4 mag”.

The strongest recent objection to MMRD came when Kasliwal et al. (2011) achieved a major breakthrough with their monitoring of M31 for novae and the resulting observational discovery of “faint, fast novae”. Their nightly cadence (except when interrupted by weather) and relatively deep magnitude limit overcame the observational bias against the discovery

of such faint, fast transients, inherent in all previous nova surveys. Rather than being rare outliers, these novae were a significant fraction of all M31 novae detected. In the past year (Shara et al. 2016) have shown that these faint, fast novae are as common in M87 as they are in M31.

In section 2 we summarise observations of well-observed novae in the Milky Way, LMC, M31, M33 and M87. We plot the maximum luminosities of novae in these five galaxies versus t_2 , the time to decline 2 magnitudes, in section 3, showing that the MMRD should be discarded as a distance indicator. In section 4 we use the extensive grid of nova models in Yaron et al. (2005) to explain the observed large observational scatter in the MMRD, and determine which nova parameters give rise to faint, fast novae. We predict the existence of ultrafast novae with $t_2 < 1$ day in section 5. Our conclusions are summarised in section 6.

2. Observations

A compilation of the peak magnitudes and distances to, and hence peak luminosities of 28 Galactic novae is given by Downes & Duerbeck (2000). These authors used ground-based and HST images of shells, and a mix of their own and literature spectroscopic expansion velocities, to determine expansion parallax distances to the largest, uniformly analysed sample of Milky Way novae in the literature. We adopt their absolute magnitudes and t_2 times to decline from maximum brightness for Milky Way novae, and add the Galactic symbiotic nova T CrB because of its equally well determined absolute magnitude (see below). Uncertainties in interstellar reddening are the greatest uncertainty in the Downes & Duerbeck (2000) study. This uncertainty adds vertical (magnitude) scatter to the data, but it cannot selectively hide faint-fast novae.

The then state-of-the-art photographic studies of the LMC were summarised in Capaccioli et al. (1990). Only 4 novae, at that time, had well-defined (i.e. directly observed, and NOT extrapolated or guessed at) times and magnitudes at maximum light. That entire sample, including the large majority of novae with extrapolated maximum magnitudes and rates of decline, did not detect faint, fast novae. As already noted, Hearnshaw et al. (2004) expressed doubts about the MMRD on the basis of new observations of fast LMC novae. The most recent summary of LMC novae is that of Shafter (2013). Four more novae with well defined times of maximum (within 2 days), maximum magnitudes and decline times have been observed in the 23 years since Capaccioli et al. (1990). These 8 well-observed LMC novae are included in our figures described below.

The only long baseline, high cadence, CCD-based survey of the Magellanic Clouds is that

of Mróz et al. (2016). Five of their 15 novae with extremely well-defined decline times fall in the faint-fast regime (particularly LMCN 2010-11a and LMCN 2012-03a). Unfortunately their CCD saturates in the magnitude range 11-12, depending on seeing (Mroz 2016, private communication). To be conservative we do not include the Mróz et al. (2016) data in our figures below.

The then state-of-the-art photographic studies of M31 novae were summarised in Capaccioli et al. (1989). Unfortunately, the original photometry has not been published, so it is impossible to judge how far they have extrapolated the maximum magnitudes, or how well-determined are the rates of decline. Faint, fast novae are absent from the data. The Shafter et al. (2011) spectrographic survey of M31 novae summarised the previous decade’s photometry of the best studied objects. We include 11 novae with well-defined V-band maxima and t_2 in our figures. Kasliwal et al. (2011) used the robotic Palomar 60-inch telescope to sample M31 in single (g) filter images in 2008 and 2009, with high cadence, and spectroscopically confirmed several of the transients they discovered as classical novae. We adopt Kasliwal et al. (2011)’s “best-observed” sample of six faint, fast novae for comparison with our own HST observations of M87 novae.

We carried out daily *Hubble Space Telescope*/Advanced Camera for Surveys (HST/ACS) imaging of the giant elliptical galaxy M87 in the F606W (V band) and F814W (I band) filters taken for HST Cycle-14 program 10543 (PI - E. Baltz) over the 72 day interval 24 December 2005 through 5 March 2006, with a few 5-day gaps at the end of the run. Full details of the observations, data reductions, detections and characterisations of 32 certain and 9 likely novae are given in Shara et al. (2016). Figures 1 and 2 of that paper include the daily images of each nova, and their full light and color curves, respectively. This survey for extragalactic novae is unprecedented, because HST observations rule out gaps due to weather, and there are no variations in limiting magnitude due to variable seeing or lunar phase. Thus 21 novae were detected both before and after maximum light, and their brightnesses were measured within 12 hours of maximum light. Our daily sampling over a 10 week span was deep enough to be almost impervious to M87’s background light, revealing novae to within 10” of the galaxy’s nucleus. In addition, novae were detected over a nearly 6 magnitude range of brightness, so that even the faintest and fastest of novae were easily detected.

3. Milky Way, LMC, M33, M31 and M87 MMRD data

In Figure 1 we plot the MMRD diagram of all the Galactic novae with expansion parallax distances from the Downes & Duerbeck (2000) study of novae. To these we add T CrB, the symbiotic nova with a similarly reliable distance and absolute magnitude. For T CrB, t_2

is taken from Schaefer (2010), while the distance is measured from the known radius of its Roche lobe-filling red giant, its well-studied orbit, and its angular radius from optical (K-band) interferometry Mikołajewska (2016). We also plot the most reliable (i.e. with very well determined maximum brightnesses and t_2) novae in the LMC and M33; the rapidly recurring nova M31 -12a in M31 (Darnley et al. 2016); the best observed faint-fast novae in M31 (Kasliwal et al. 2011); and the 21 novae from our HST survey of M87.

Our complete sample of M87 novae not only supports the Kasliwal et al. (2011) claim that faint, fast novae exist, but triples the sample of such objects, and adds three of the fastest examples known. These three novae, with t_2 of 2.01, 3.72 and 3.75 days, are comparable to V597 Pup (Hounsell et al. 2016), and the extraordinary recurrent nova M31-12a in the Andromeda galaxy, which erupts twice every year (Henze et al. 2015) and fades by 2 magnitudes in just 1.65 days (Darnley et al. 2016). A few novae in M31 and elsewhere have been seen with similar values of t_2 , but almost always with $M = -9.5$ to -10 rather than the values of -7 to -8 observed in M87 and in T CrB.

It is clear from Figure 1 that novae, long believed to be “standard candles”, display three magnitudes of dispersion in the magnitudes of their MMRD diagram when high cadence, deep CCD sampling is used so as not to exclude faint, fast novae. They cannot be reliably used to measure extragalactic distances, or the distances of newly-discovered Galactic novae. This strengthens the similar conclusion reached by Ferrarese et al. (2003), albeit based on a smaller and less densely sampled group of nine novae in M49, and by Kasliwal et al. (2011) on the basis of the faint, fast novae they detected in M31.

Why did the roughly 100 Galactic, LMC, SMC and M31 novae of the previous century and noted in section 2, provide MMRDs that yielded a few good extragalactic distances? The surveys that located these objects all suffered from the same incompleteness. The relatively easy-to-find classical novae populate, in zeroth approximation, the upper left and lower right quadrants of MMRD plots. The upper right quadrant is mostly empty (very slow, very bright novae are rare), while the hard-to-find objects in the lower left quadrant (faint and fast) were almost all missed. The preferential detection of novae in only the upper left and lower right quadrants suggested a spurious correlation - bright objects are preferentially fast and faint objects are slow. Once the lower left quadrant was filled in (with 40% of all novae) - as has now happened - the apparent correlation vanished.

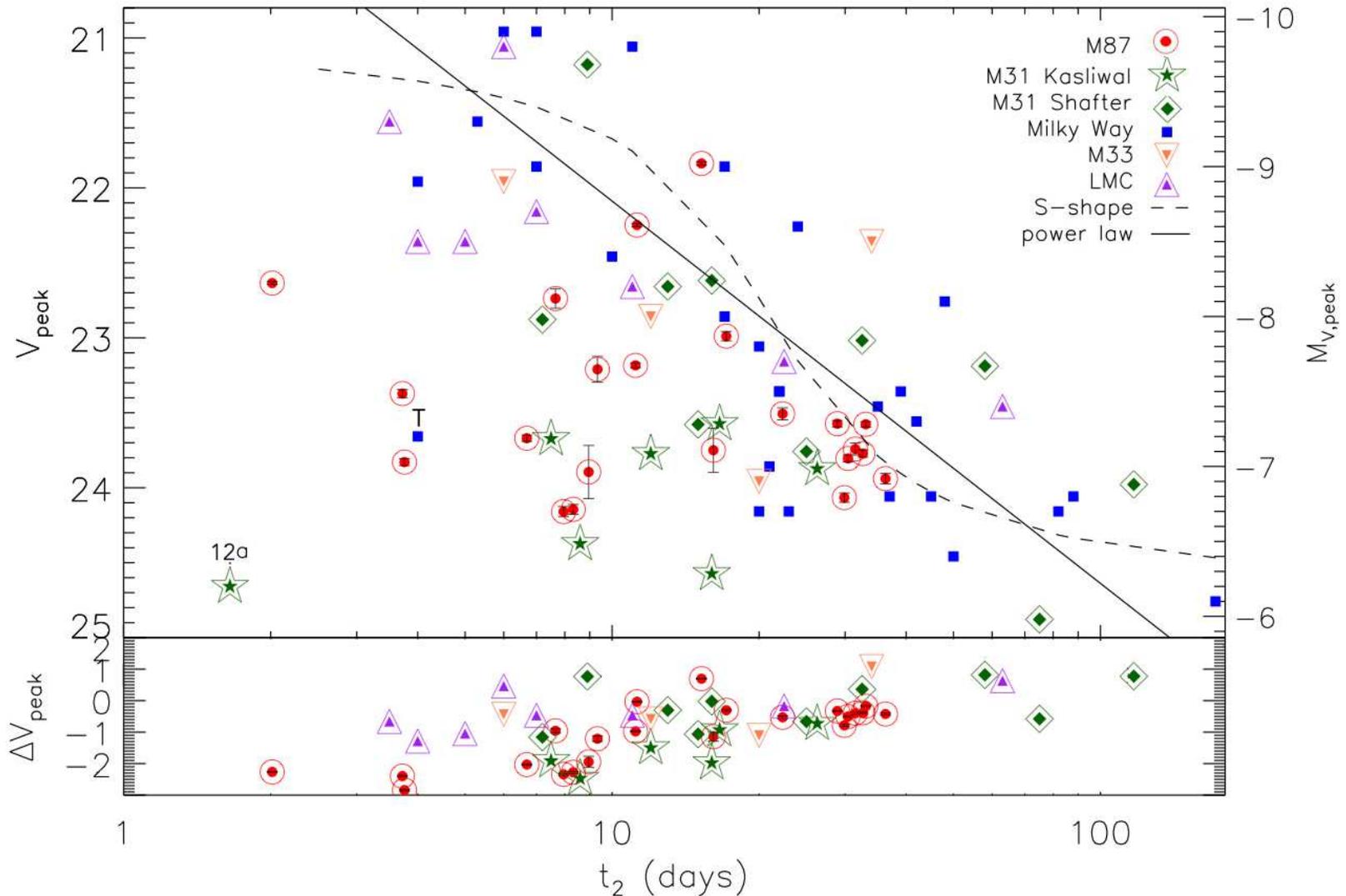


Fig. 1.— Maximum magnitude - Rate of Decline relation (MMRD) for novae with well-defined maxima and t_2 in the Milky Way (MW), LMC, M33, M31 and M87. t_2 is the time it takes a nova to decline 2 magnitudes from its peak brightness. Filled squares represent MW novae from Downes & Duerbeck (2000), T denotes the symbiotic nova T CrB (Schaefer 2010; Mikolajewska 2016), upright triangles are LMC novae from Shafter (2013), inverted triangles are M33 novae from Shafter et al. (2012), 12a refers to M31 - 12a (Darnley et al. 2016), open/filled stars denote M31 novae from Kasliwal et al. (2011) and Shafter et al. (2011), and open/filled circles denote M87 novae from Shara et al. (2016). The M31 data were transformed using transformations from g to V of Jordi et al. (2006). The solid and dashed lines represent the best fit power law and S-shaped curves for MW novae (Downes & Duerbeck 2000). The deviation of each nova from the S-shaped curve in Figure 1 is plotted in the figure's lower panel.

4. Why is there so much scatter in the MMRD plot?

We have already noted that the mass of the WD in a nova binary is predicted to be an important parameter in determining how quickly a nova ejects its hydrogen-rich envelope, and thus how fast it declines from maximum light. This is quantifiable via the 75 self-consistent models of novae of Yaron et al. (2005), which not only varied WD mass, but also WD luminosity and accretion rate onto WDs. Kasliwal et al. (2011) plotted all these models in an M_V - timescale diagram, and concluded that “Some hot and massive white dwarfs with high accretion rates can result in a faint and fast nova population consistent with the P60-FasTING sample.” We now show that *low* accretion rates, and especially *low accreted envelopes masses*, are equally effective at creating faint, fast, *non-recurrent* novae on massive WDs.

To clearly separate each of the parameters that determine the location of a nova model in the M_V - t_2 diagram, we superpose onto Figure 1 all 75 of the Yaron et al. (2005) models, color-coded by WD mass (Figure 2), mass accretion rate (Figure 3), WD core temperature (Figure 4) and total accreted envelope mass (Figure 5). We note that the Yaron et al. (2005) models calculate t_3 (as the timescale of mass-loss t_{ml}) rather than t_2 ; we assume that t_2 is simply two-thirds of t_3 . Like Kasliwal et al. (2011), we assume that novae at maximum luminosity display spectral types close to A5V to convert the Yaron et al. (2005) maximum model luminosities to M_V . The models depicted in Figure 2 (and those in Hillman et al. (2016)) predict that any nova displaying $t_2 < 10$ days must contain a WD with a mass in excess of $1.25 M_\odot$. Two of Kasliwal et al. (2011)’s six best-observed M31 novae display $t_2 < 10$ days, while nine of the 21 novae we detected in M87 with well-determined values of t_2 do the same. While the Shara et al. (2016) survey of M87, spanning 72 days, is ineffective at identifying novae with t_2 longer than 50-60 days, it is clear from their Figure 12 that over 40% of fast novae display $t_2 < 10$ days. Such objects are certainly not rare, and reaffirm the claims that WD masses in nova binaries are much larger, on average, than those in the field (Ritter et al. 1991; Pagnotta & Schaefer 2014).

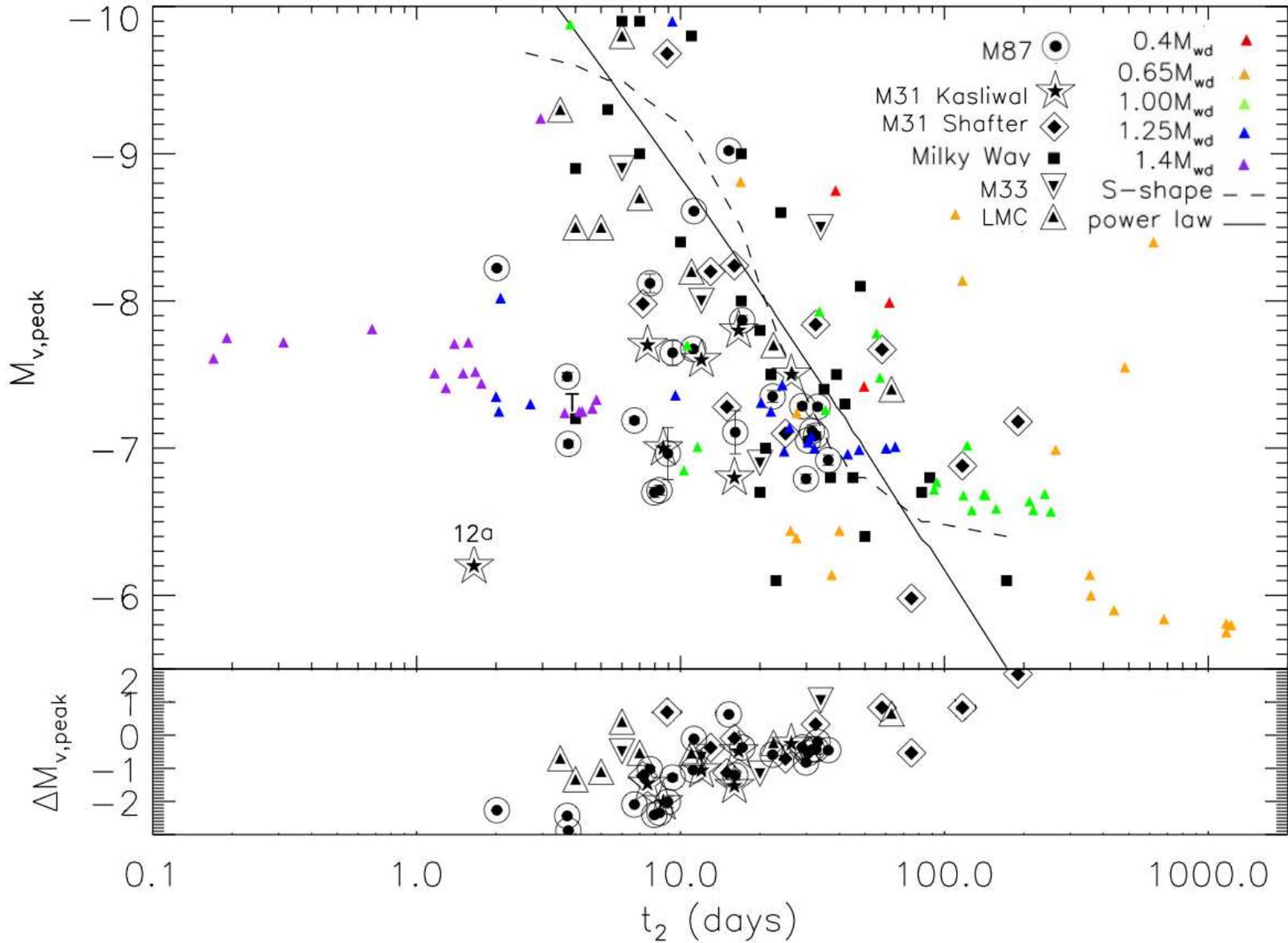


Fig. 2.— Same as Figure 1, but including 75 nova models from Yaron et al. (2005), as triangles colored according to the mass of the white dwarf in the nova binary. Larger mass white dwarfs, as explained in the text, correlate with shorter t_2 . The masses of the WDs of the six faint, fast novae discovered by Kasliwal et al. (2011) (stars in the figure) are probably in the range 1.0 - 1.25 M_{\odot} , while the three fastest novae detected in M87 by Shara et al. (2016) must contain white dwarfs close to the Chandrasekhar mass.

It is certainly true that varying the rate of mass accretion onto a WD of given mass in a nova binary can lead to very different outcomes (Paczynski & Zytlow 1978; Prialnik et al. 1982). In particular, one might guess that, after WD mass, mass accretion rate is the most important parameter determining the properties of a nova. In Figure 3 we again replot the 75 nova models of Yaron et al. (2005) on the observational MMRD diagram of Figure 1, but this time the models are color-coded according to mass accretion rate. In sharp contrast with Figure 2, where it is apparent that WD mass and t_2 are strongly correlated, Figure 3 demonstrates that mass accretion rate and t_2 are not correlated at all. Accretion rates of $10^{-12.3}M_{\odot}/\text{yr}$ can produce novae with t_2 as small as 0.2 days or as large as 500 days. Peak luminosities, for this same accretion rate, range from $M_V = -6.5$ to -9.8 . Similar large ranges are seen in both M_V and t_2 for other values of the mass accretion rate. A similar result is seen in Figure 4, where we replot the 75 Yaron et al. (2005) models again, but color-coded for WD core temperature (and thus WD luminosity). WD luminosity by itself plays very little role, if any, in determining the luminosities or decline times of novae.

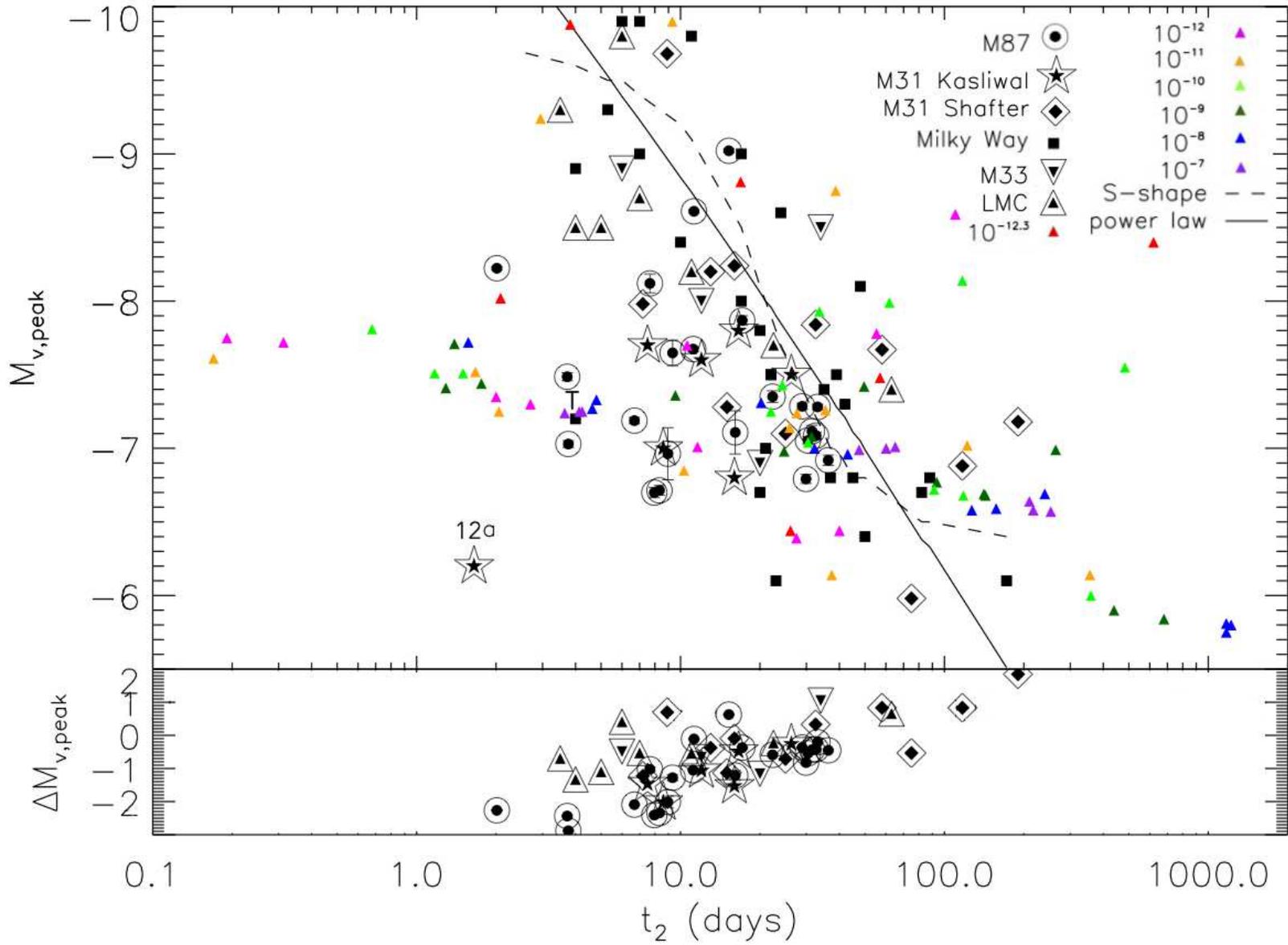


Fig. 3.— Same as Figure 1, but including 75 nova models from Yaron et al. (2005), as triangles colored according to the mass accretion rate (assumed constant) onto the white dwarf. Mass accretion rates differing by several orders of magnitude can produce identical values of t_2 or peak luminosity.

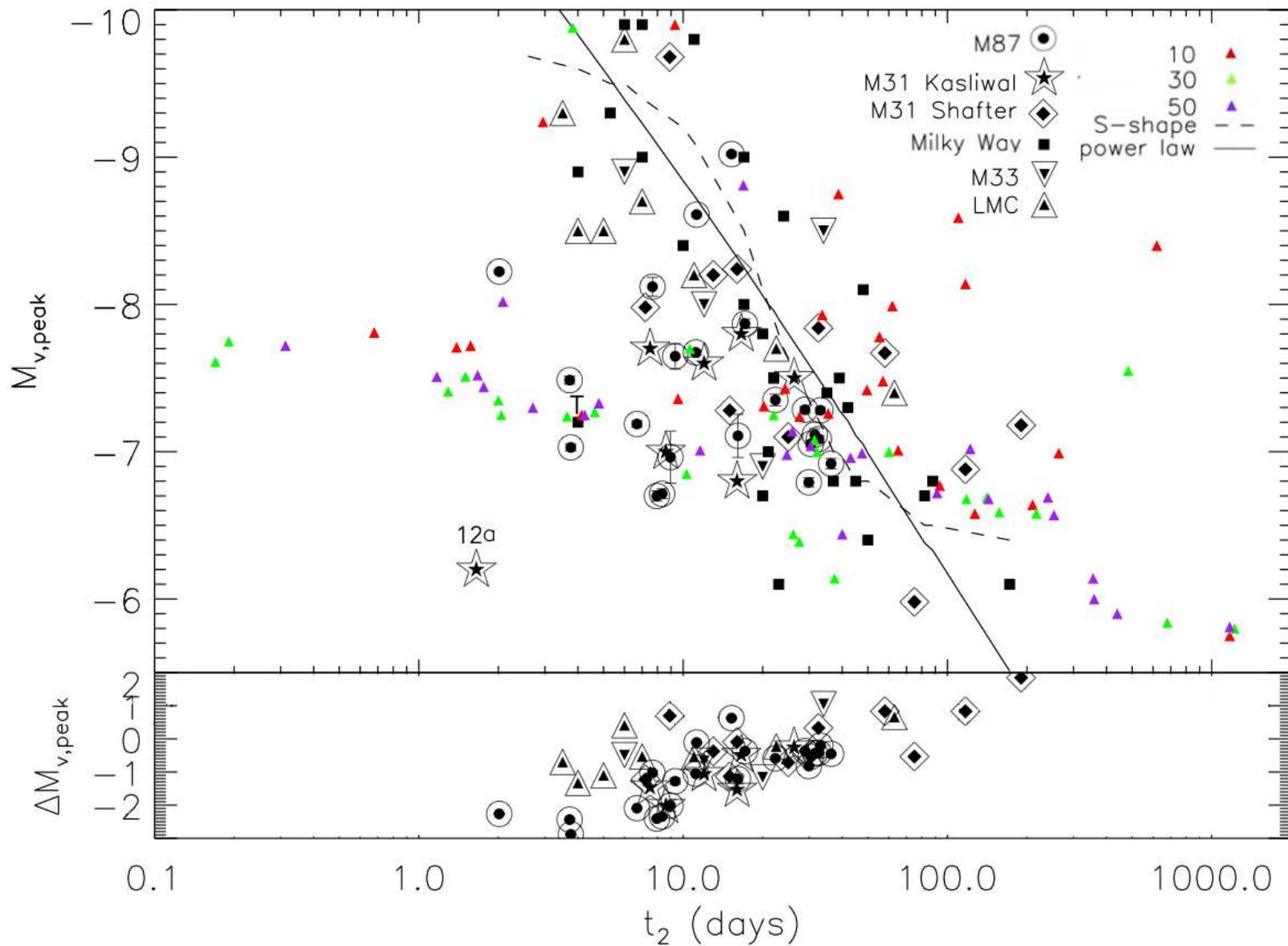


Fig. 4.— Same as Figure 1, but including 75 nova models from Yaron et al. (2005), as triangles colored according to the WD core temperature (in units of millions of Kelvins), and hence the luminosity of the white dwarf in the nova binary.

The inconclusive results of Figures 3 and 4 are resolved in Figure 5, where we again plot the Yaron et al. (2005) nova models, but now color-coded according to the mass of the hydrogen-rich envelope accreted before a nova TNR begins. The correlation between t_2 and accreted envelope mass is evidently much stronger than the correlations of WD luminosity or mass accretion rate with t_2 . This is even more obvious in Figure 6, where we plot the accretion rate, WD temperature, and accreted envelope mass versus t_2 . A useful empirical equation relating these latter two quantities is the least square fit straight line

$$\log M_{env} = 0.825 \log (t_2) - 6.108 .$$

The underlying reason for the behaviour in Figure 6 is simple: the smallest envelope masses can be ejected the most quickly, leading to the smallest observed t_2 .

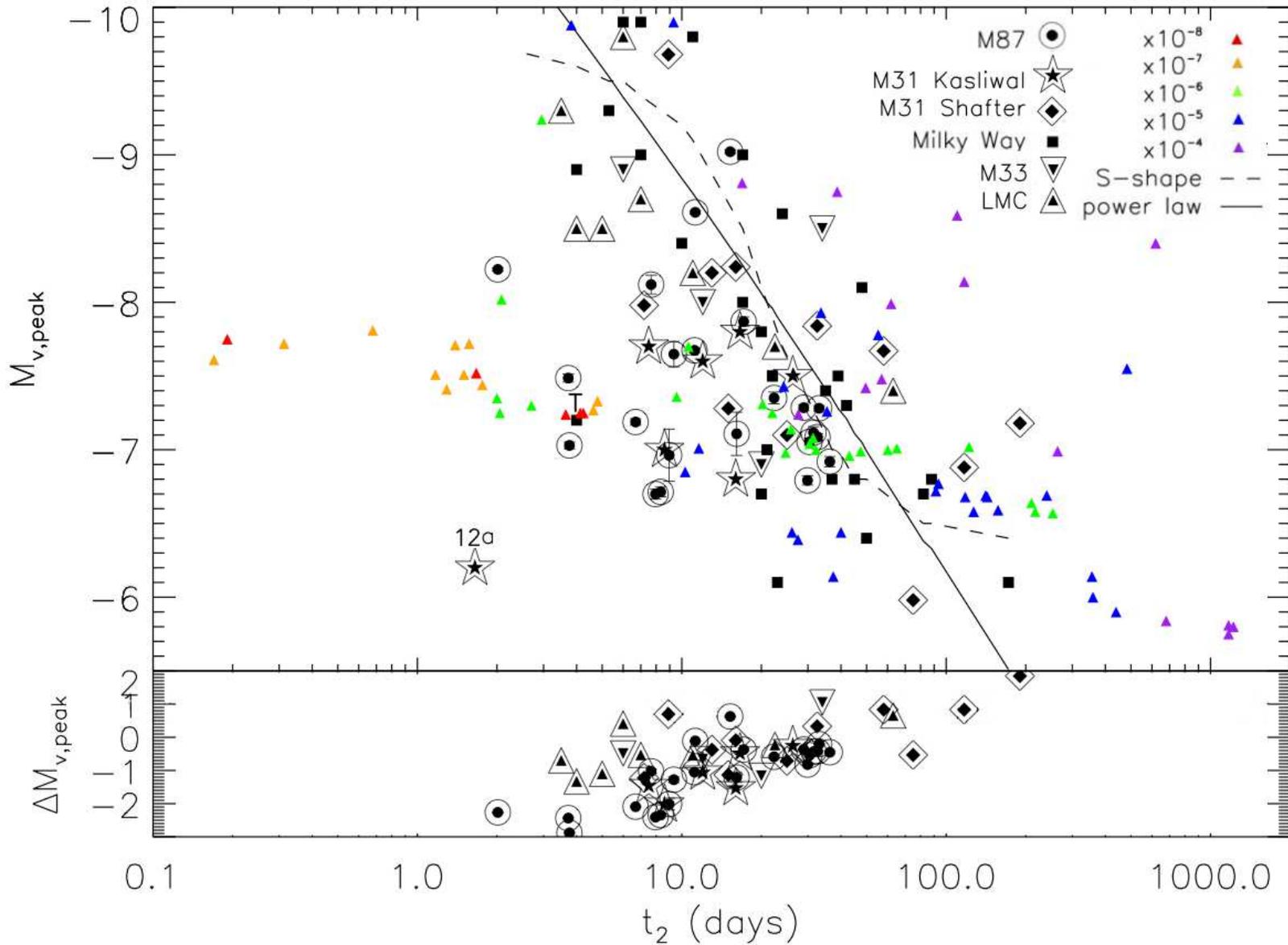


Fig. 5.— Same as Figure 1, but including 75 nova models from Yaron et al. (2005), as triangles colored according to the total hydrogen-rich mass accreted onto the white dwarf in the nova binary. The fastest novae (with smallest t_2) have accreted the lowest mass hydrogen-rich envelopes - $10^{-7} - 10^{-8}M_{\odot}$ - while the slowest novae (largest t_2) have accreted envelopes 1,000 -10,000 times more massive. From this figure, and Figure 2, it is clear that the total accreted envelope mass is as critical a parameter as the WD mass in determining the peak luminosity and t_2 of a nova.

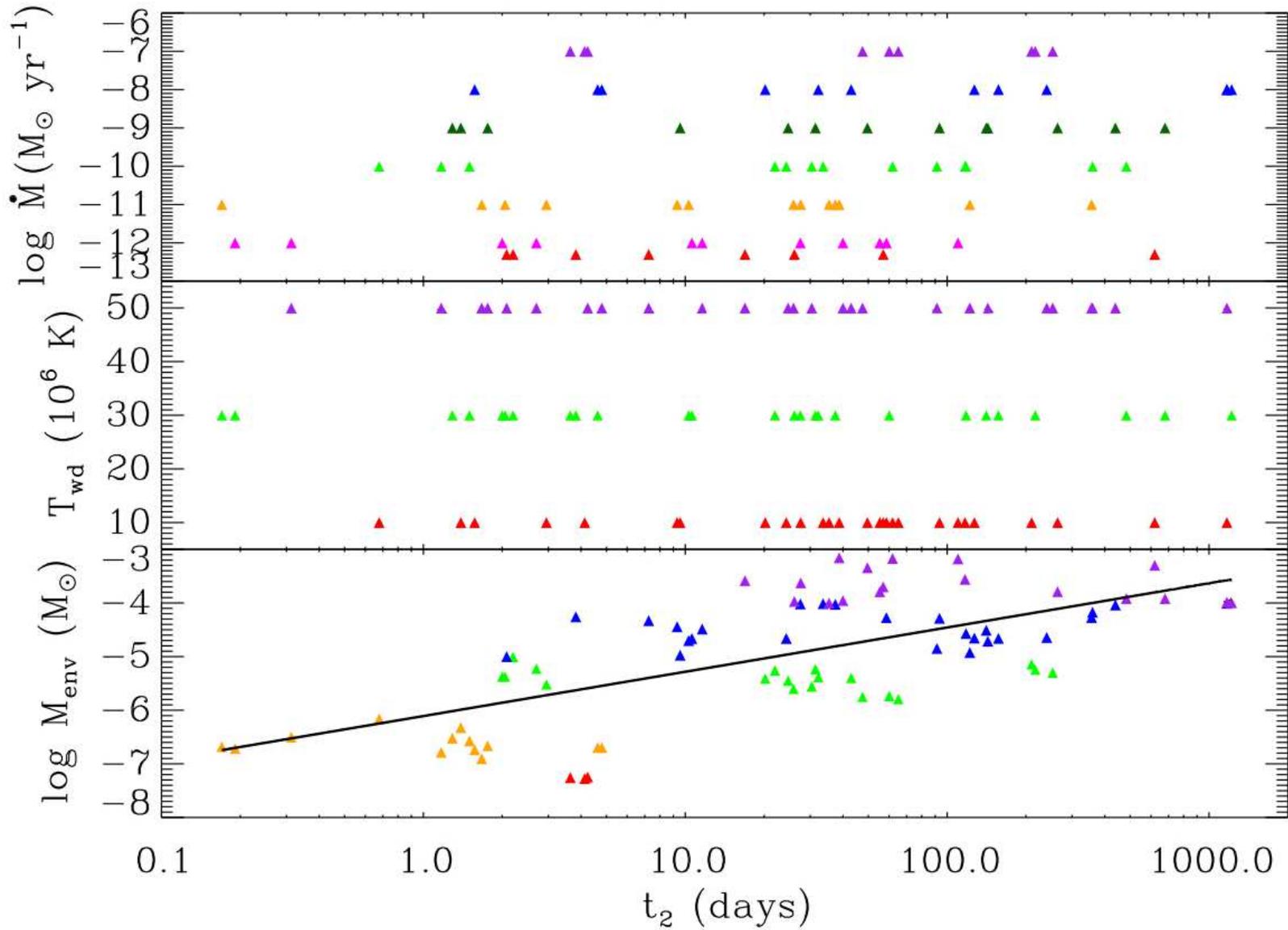


Fig. 6.— Mass accretion rate, WD temperature and accreted envelope mass at the time of eruption, versus t_2 , for 75 nova models from Yaron et al. (2005). The colors of triangles in the top, middle and lower panels correspond to the symbols' keys in Figures 3, 4 and 5. The least-squares fit straight line in the lower panel is discussed in the text.

5. A Prediction: the Existence and Detection of Ultrafast Novae

A strong and testable prediction, overlooked until now, emerges from the models of Yaron et al. (2005) that is evident in, and physically understandable from Figures 2, 4, 5 and 6. *We predict that WDs with masses close to $1.4 M_{\odot}$, which have slowly ($10^{-10} - 10^{-12.3} M_{\odot}/yr$) accreted envelopes of low mass ($10^{-7} - 10^{-8} M_{\odot}$) can produce novae with t_2 as short as 5 hours.* Simulated light curves of such novae are shown in Figure 4 of Hillman et al. (2014).

We (rather arbitrarily) define an ultrafast nova as one which displays $t_2 < 1$ day. No such nova has ever been observed, but we maintain that this is entirely due to sampling bias. Every ground-based survey for extragalactic novae reported in the past century has employed cadences of a day or longer. Even our own M87 nova survey, which successfully sampled that galaxy daily for 10 weeks without gaps, was unlikely to find any nova that appeared and then faded by 2 magnitudes in less than one day, let alone in 5 hours.

High accretion rates can accumulate critical envelope masses on timescales as short as years Yaron et al. (2005). This is the source of the Recurrent Novae (RNe), which have massive WDs and inter-eruption intervals of a century or less. Examples include M31-12a and T CrB. RNe have recently been estimated to comprise 25% of all novae (Pagnotta & Schaefer 2014). We emphasize that (still hypothetical) ultrafast novae are not RNe. Their low accretion rates must inevitably lead to millennia or longer between their eruptions. If ultrafast novae are eventually detected, we predict that their ejecta will be very significantly enhanced in nitrogen relative to the solar value. This is because the long timescale needed to bring these slowly accreted envelopes to the critical mass for initiation of a TNR will allow for significant diffusion of hydrogen into the underlying WD (Kovetz & Prialnik 1985). This mixing enriches the burning envelope of novae by an order of magnitude or more in CNO isotopes, which are mostly converted to nitrogen by the TNR.

RNe do not fit the classical nova MMRD (Schaefer 2010). But if astronomers are to use MMRD, and to have any confidence in the use of the MMRD for novae discovered in the future, one must be able to distinguish a newly-discovered nova as being a RN or a Classical Nova. (By RN we adopt the conventional definition: an RN erupts at least once per century). Pagnotta & Schaefer (2014) have exhaustively researched this topic, and demonstrated that the only certain diagnostic of a nova being a RN is observing a second outburst. Thus any newly discovered, fast Galactic or extragalactic nova could be faint and fast (and relatively close), or luminous and fast (and relatively distant). MMRD alone cannot yield a reliable distance for any nova with $t_2 < 30$ days. Slower novae all display $M = -6.5 \pm 0.5$ mag, but this is almost independent of t_2 and the MMRD.

Are ultrafast novae rare? A reliable theoretical prediction of the frequency of ultrafast novae relative to all other novae in a galaxy would involve a population synthesis model which produces novae from an initial and evolving binary population, and self-consistently calculates the time-dependent mass transfer rate to the WD in each nova system over that system’s lifetime. This is a challenging problem, far beyond the scope of this paper. A much simpler approach is to observationally detect ultrafast novae, and measure their relative frequency amongst all novae.

How might ultrafast novae be detected? The answer is straightforward: via surveys of nearby galaxies with cadences of order one hour, rather than days. Figure 2 demonstrates that ultrafast novae should achieve M_V of -6.5 to -7.5, corresponding to 17-18th magnitude in M31. Detecting such rapid transients, and following them down to 20th magnitude, is within the reach of modern CCD cameras attached to 0.5 meter aperture telescopes. The Zwicky Transient Facility (ZTF) will utilize a large format camera and the Samuel Oschin 48-inch Palomar Schmidt telescope to begin imaging about 3750 square degrees an hour to a depth of 20.5-21 magnitude in 2017. With a 1-hour cadence it should easily discover ultrafast novae in Local Group galaxies. Confirmation, via spectroscopy or narrowband-broadband imaging, can be done in the days following the detection of rapid transient candidates, as novae remain bright in $H\alpha$ for much longer than they do in continuum light (Ciardullo et al. 1983; Neill & Shara 2004).

6. Summary and Conclusions

Nine of 21 well-observed novae in M87 display t_2 brightness decline times under 10 days, and three more have $t_2 < 4$ days. These novae are up to 3 magnitudes fainter than predicted by the MMRD relation, and are similar to the “faint, fast novae” first detected by Kasliwal et al. (2011) in M31. The fact that these novae are both common and ubiquitous demonstrates that complete samples of extragalactic novae are not reliable standard candles, and that the MMRD should not be used in the era of precision cosmology either for cosmic distance determinations or the distances of Galactic novae.

The Yaron et al. (2005) models of novae explain faint, fast novae as those which occur on very massive WDs, with very low mass envelopes. Low mass envelopes that were accreted quickly lead to RNe. We predict that those accreted slowly yield (previously overlooked) ultrafast novae which brighten and fade by 2 magnitudes in under 1 day. Such ultrafast novae are also predicted to display large nitrogen enhancements relative to the solar value. We predict that surveys of M31 and other nearby galaxies with cadences of order 1 hour will reveal these novae, even with modest-sized telescopes.

We gratefully acknowledge the support of the STScI team responsible for ensuring timely and accurate implementation of our M87 program. Support for program #10543 was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. This research has been partly supported by the Polish NCN grant DEC-2013/10/M/ST9/00086. MMS gratefully acknowledges the support of Ethel Lipsitz and the late Hilary Lipsitz, longtime friends of the AMNH Astrophysics department.

REFERENCES

- Arp, H.C. 1956, *AJ*, 61, 15
- Baade, W. 1944, *ApJ*, 100, 137
- Bird, S., Harris, W. E., Blakeslee, J. P., & Flynn, C. 2010, *A&A*, 524, A71
- Capaccioli, M., della Valle, M., Rosino, L., & D’Onofrio, M. 1989, *AJ*, 97, 1622
- Capaccioli, M., della Valle, M., D’Onofrio, M., & Rosino, L. 1990, *ApJ*, 360, 63
- Chandrasekhar, S. 1931, *ApJ*, 74, 81
- Chandrasekhar, S. 1935, *MNRAS*, 95, 207
- Christy, R. F. 1966, *ApJ*, 144, 108
- Ciardullo, R., Ford, H., & Jacoby, G. 1983, *ApJ*, 272, 92
- Ciardullo, R., Jacoby, G. H., Ford, H. C., & Neill, J. D. 1989, *ApJ*, 339, 53
- Cohen, J. G. 1985, *ApJ*, 292, 90
- Darnley, M. J., Henze, M., Bode, M. F., et al. 2016, *ApJ*, 833, 149
- de Grijs, R., & Bono, G. 2014, *AJ*, 148, 17
- della Valle, M., & Livio, M. 1995, *ApJ*, 452, 704
- Downes, R. A., & Duerbeck, H. W. 2000, *AJ*, 120, 2007
- Faulkner, J., Flannery, B. P., & Warner, B. 1972, *ApJ*, 175, L79
- Ferrarese, L., Côté, P., & Jordán, A. 2003, *ApJ*, 599, 1302
- Hearnshaw, J. B., Livingston, C. M., Gilmore, A. C., & Kilmartin, P. M. 2004, *IAU Colloq. 193: Variable Stars in the Local Group*, 310, 103
- Henze, M., Darnley, M. J., Kabashima, F., et al. 2015, *A&A*, 582, L8
- Hillman, Y., Prialnik, D., Kovetz, A., Shara, M. M., & Neill, J. D. 2014, *MNRAS*, 437, 1962
- Hillman, Y., Prialnik, D., Kovetz, A., & Shara, M. M. 2016, *ApJ*, 819, 168
- Hounsell, R., Darnley, M. J., Bode, M. F., et al. 2016, *ApJ*, 820, 104

- Hubble, E. 1929, *ApJ*, 69, 103
- Hubble, E. 1929, *Proceedings of the National Academy of Science*, 15, 168
- Inno, L., Bono, G., Matsunaga, N., et al. 2016, *ApJ*, 832, 176
- Jordi, K., Grebel, E. K., & Ammon, K. 2006, *A&A*, 460, 339
- Kasliwal, M. M., Cenko, S. B., Kulkarni, S. R., et al. 2011, *ApJ*, 735, 94
- Kovetz, A., & Prialnik, D. 1985, *ApJ*, 291, 812
- Livio, M. 1992, *ApJ*, 393, 516
- Mclaughlin, D. B. 1945, *PASP*, 57, 69
- Mikołajewska, J., private communication
- Mróz, P., Udalski, A., Poleski, R., et al. 2016, *ApJS*, 222, 9
- Neill, J. D., & Shara, M. M. 2004, *AJ*, 127, 816
- Paczynski, B., & Zytkow, A. N. 1978, *ApJ*, 222, 604
- Pagnotta, A., & Schaefer, B. E. 2014, *ApJ*, 788, 164
- Prialnik, D., Livio, M., Shaviv, G., & Kovetz, A. 1982, *ApJ*, 257, 312
- Prialnik, D., & Kovetz, A. 1984, *ApJ*, 281, 367
- Prialnik, D., & Kovetz, A. 1995, *ApJ*, 445, 789
- Riess, A. G., Macri, L., Casertano, S., et al. 2011, *ApJ*, 730, 119
- Ritter, H., Politano, M., Livio, M., & Webbink, R. F. 1991, *ApJ*, 376, 177
- Sandage, A. R. 1971, *Study Week on Nuclei of Galaxies*, Amsterdam: North Holland, ed. D.J.K O’Connell, 601
- Schaefer, B. E. 2010, *ApJS*, 187, 275
- Shafter, A. W., Darnley, M. J., Hornoch, K., et al. 2011, *ApJ*, 734, 12
- Shafter, A. W., Darnley, M. J., Bode, M. F., & Ciardullo, R. 2012, *ApJ*, 752, 156
- Shafter, A. W. 2013, *AJ*, 145, 117

- Shara, M. M., Prialnik, D., & Shaviv, G. 1980, *ApJ*, 239, 586
- Shara, M. M. 1981, *ApJ*, 243, 926
- Shara, M. M., Doyle, T. F., Lauer, T. R., et al. 2016, *ApJS*, 227, 1
- Starrfield, S. G., Sparks, W. M., & Truran, J. W. 1975, *Memoires of the Societe Royale des Sciences de Liege*, 8, 425
- Starrfield, S., Sparks, W. M., & Truran, J. W. 1986, *ApJ*, 303, L5
- van den Bergh, S. 1992, *PASP*, 104, 861
- Warner, B. 1995, *Cambridge Astrophysics Series*, 28
- Yaron, O., Prialnik, D., Shara, M. M., & Kovetz, A. 2005, *ApJ*, 623, 398
- Zwicky, F. 1936, *PASP*, 48, 191