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Extragalactic novae

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14.1 Introductory remarks

Observations of extragalactic novae date back to the early twentieth century, and were influential in the debate concerning the nature of the spiral nebulae (see van den Bergh 1988 for a review of the early history). Initially, the identification of extragalactic novae was fraught with confusion, as the distinction between classical novae, with typical absolute magnitudes ranging from $M_{\rm pg} \sim -7$ to $M_{\rm pg} \sim -9$, and supernovae, which are of order ten thousand times more luminous, was not yet appreciated. The most well known example of this confusion concerns the report by Hartwig (1885) of a 'nova' in the great nebula in Andromeda. This object, S And, is now recognized as the first and only supernova to be observed in M31. Just a decade later another bright star was discovered very near the spiral nebula NGC 5253 by Fleming during her examination of Draper Memorial photographs (Pickering & Fleming, 1896). This object, Z Cen, is also now recognized as a supernova (SN 1895B). No additional nova candidates were associated with spiral nebulae until the discovery on 19 July 1917 by Ritchey (1917a) of a 14th magnitude transient star in the outer portion of NGC 6946. This discovery set off a systematic search of archival plates from the Mt Wilson 1.5m reflector dating back to 1908. By the end of 1917, a total of eleven 'novae', or 'temporary stars', as they were sometimes called, had been identified in various spiral nebulae (Shapley, 1917). Of these objects, one turned out to be a Galactic variable star not associated with an extragalactic nebula, seven, including Ritchey's 1917 nova, Z Cen, and S And, are now recognized as supernovae. The remaining three were in fact bona fide classical novae in M31, and represent the first true discoveries of classical novae outside the Milky Way. The credit for the initial discovery goes to Ritchey (1917b) for his re-examination of the first Mt Wilson 1.5m plates of M31 taken back in August and September of 1909. Remarkably, two novae were identified, both of which were recorded at maximum light on 16 September 1909. During the period between 1917 and 1922 an additional 19 novae were discovered during sporadic monitoring of M31.

The potential role of novae as extragalactic distance indicators was recognized early on. Shapley (1917), in his 'Notes on the Magnitudes of Novae in Spiral Nebulae', was already contemplating the potential ramifications of placing the Andromeda nebula at a distance of $\sim$50 times that of the average Galactic nova, as suggested by a comparison of the apparent magnitudes of Galactic and M31 novae (with the one exception of S And). The minimum luminosity implied for S And, $M \sim -15$, was considered fantastical at the time. In the end, the difficulty in reconciling the enormous luminosity implied for S And, coupled with the perceived difficulty in reconciling van Maanen's (erroneous) measurement of internal proper motion in M101 with its extragalactic nature, led Shapely to seriously question the 'island universe' interpretation of the spiral nebulae.

The role of novae in measuring extragalactic distances was further developed by Lundmark (1922) in his work to calibrate the absolute magnitudes of Galactic novae. Based on rather uncertain parallax measurements of 10 Galactic novae (only seven of which are now recognized as classical novae), Lundmark estimated a mean absolute magnitude of $M_{\rm pg} = -6.2$. In a later paper Lundmark (1923) summarized much of what was known about Galactic novae up to that time, which included an interesting comparison between the apparent magnitudes at maximum of Galactic novae with those in the field of the Andromeda nebula*. Specifically, by comparing the apparent magnitudes of novae in the Sagittarius region of the Milky Way (which displayed a relatively small dispersion) and those novae (excluding S And) discovered in the Andromeda nebula, he estimated that M31 was approximately 9 mag fainter (a factor of $\sim$60 more distant) than the Sagittarius novae. Thus, taking a modern estimate of 8 kpc to the Galactic center (Gwinn, Moran & Reid, 1992) yields a distance to M31 of $\sim$ 500 kpc, which is in closer agreement with the modern value of 765 kpc (Freedman et al., 2001) than Hubble's 1929 Cepheid distance of 275 kpc. Indeed, if not for the confusion between novae and supernovae, the distance to M31 would have likely been determined first (and more accurately) through the use of novae.

Starting in the autumn of 1923, Hubble began an annual monitoring program to study the statistical properties of novae in M31. This program, which by 1927 had identified an additional 63 objects in M31, represented the first systematic study of extragalactic novae. Hubble's early work established several properties of M31 novae that are still accepted today. Specifically, novae exhibited a frequency distribution at maximum light characterized by $\langle m_{\rm pg} \rangle \simeq 16.5$, and a spatial distribution that generally follows the nebular light. Remarkably, Hubble deduced an overall nova rate for the galaxy of $\sim$30 yr^{-1}, which is in excellent agreement with virtually all subsequent studies (Arp, 1956; Capaccioli et al., 1989; Shafter & Irby, 2001). Although Hubble's inaccurate Cepheid-based distance to M31 caused him to underestimate the luminosities of M31 novae by $\sim$ 2 mag, his observations clearly established their similarity to Galactic novae, while clearly distinguishing normal novae from anomalously bright objects such as S And. Indeed, when discussing the 86 M31 novae in his classic paper on the Andromeda nebula, Hubble (1929) remarked 'The nova of 1885 is clearly an exceptional case, and the eighty-five photographic novae must be con-

* Curiously, he also noted that the amplitudes, $A(= m_{\rm min} - m_{\rm max})$, of nova outbursts are anticorrelated with $m_{\rm max}$ as shown in his Figure 3, which is not surprising, and must be true for any distance-limited sample of novae.

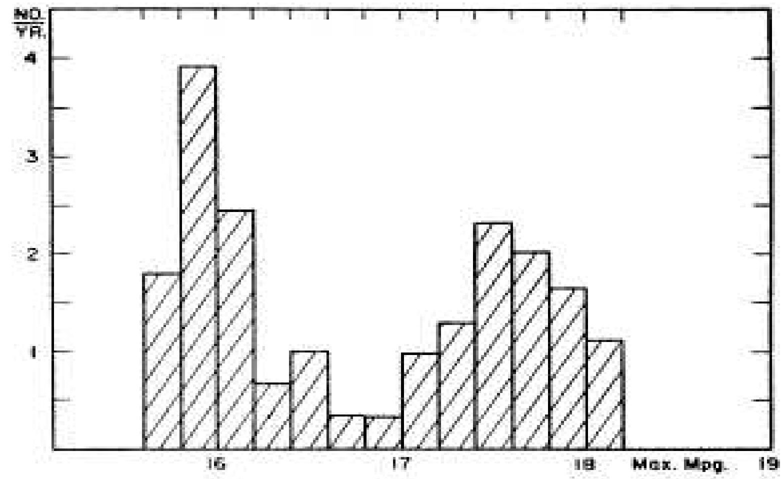

Fig. 14.1. The distribution of magnitudes at maximum light for the sample of 30 M31 novae from Arp (1956). Note the bimodal nature of the distribution with peaks near $m_{\rm pg} = 16.0$ and $m_{\rm pg} = 17.5$.

sidered as normal'. It wouldn't be for another five years before the term 'supernova' was coined by Baade & Zwicky (1934) to describe the brighter class of objects.

Although our current understanding of classical novae as arising from a thermonuclear runaway on the surface of an accreting white dwarf in a semi-detached binary system would have to await the now classic work in the 1960s and 1970s by Kraft (1964a,b), Warner & Nather (1971), and Starrfield et al. (1972) (see Chapter 4), an impressive collection of observational data on both Galactic and extragalactic novae continued to accumulate in the intervening years. The next major extragalactic nova survey following Hubble's pioneering work was a survey of M31 conducted by Arp (1956) using the 1.5m telescope on Mount Wilson. This study was remarkable in terms of the intensity of temporal coverage. Almost 1000 plates were taken on 290 nights between June 1953 and January 1955. A total of 30 novae were identified. As a result of the dense coverage, only five novae were believed to have their maxima missed by more than a day. During the two-year M31 survey, Arp photographed five other local group members: M32, NGC205, M33, NGC147, and NGC 185. The first two were included on the M31 plates, and thus received essentially the same coverage. The latter three galaxies were monitored once or twice a week. No novae were detected in any of these relatively low mass systems.

Broadly speaking, the results of Arp's M31 survey confirmed Hubble's earlier conclusions. Arp found a global nova rate of 26 ± 4 per year, a nova spatial distribution intermediate between a flattened disk and a nearly spherical bulge component, and light curve properties similar to those of Galactic novae. A particularly noteworthy finding was that the frequency distribution of nova magnitudes at maximum light was apparently bi-modal with peaks near $m_{\rm pg} = 16.0$ and $m_{\rm pg} = 17.5$ (see Fig 14.1). The bimodal nature of the distribution has been evoked in recent years in support of the intriguing possibility that there may be two populations of novae: 'bulge' novae and 'disk' novae, with the former thought to be generally less luminous and 'slower' than their 'disk' counterparts. We now turn to a discussion of the stellar population of novae.

14.2 Nova populations

The stellar population of novae has been a subject of discussion since Baade introduced the concept of stellar populations more than a half century ago (Baade, 1944). It was recognized early on that any attempt to elucidate the population of novae from their apparent Galactic space distribution will be confounded by the effects of patchy interstellar extinction. Nevertheless, several attempts were made to assign novae to a particular stellar population with no real success. Perhaps the situation was best summed up by Plaut (1965), who noted that given the apparent concentration of novae both towards the Galactic plane and the Galactic center, 'Classification according to the simple population I and II scheme is therefore somewhat ambiguous'. (Duerbeck, 1984, Table 1), gives a convenient summary of the early attempts to determine the Galactic distribution of novae up to that time. In view of the difficulties associated with Galactic observations, it is not surprising that observation of the spatial distribution of novae in external galaxies soon became the focal point in the study of the stellar population of novae.

After Arp's classic study concluded in 1955, novae continued to be discovered in M31 as part of ongoing surveys over roughly the next thirty years, primarily in Italy, Crimea and Latvia (Rosino, 1964, 1973; Rosino et al., 1989; Sharov & Alksnis, 1991). The most extensive survey was conducted at the Asiago Observatory where Rosino and collaborators discovered a total of 142 novae, some with sufficient data for light curves to be characterized. In agreement with the findings of Hubble and Arp, Rosino (1964) concluded that 'In general, the light curves of novae found at Asiago show the same variety of forms of the Galactic novae, to which they are strikingly similar'. One change in the Asiago survey concerned observations in the latter years of the survey, which were obtained through a UG1 ultraviolet filter to provide better contrast against the bright nuclear region. Despite the attempt to detect novae in the nuclear region, the nova distribution fell off significantly near the nucleus as first noted by Arp. Rosino (1973) concluded that 'the region close to the nucleus seems really devoid of novae'. Another surprising early result of the Rosino study concerned the distribution of nova magnitudes at maximum light. When the Hubble, Arp, and Asiago samples were combined, the bimodality seen in the Arp data was no longer apparent (Rosino 1973, his Figure 14)*.

Little additional progress was made in our understanding of the M31 nova populations for the next decade. Then, in the Fall of 1981, the foundations were laid for a new approach in the study of nova populations, when Ciardullo et al. (1983) discovered four anomalously bright Hα sources in on-band, off-band images taken during a search in M31's bulge for Hα-bright planetary nebulae, and other potentially interesting emission line sources, such as the then recently discovered SS433 (Margon et al., 1979). Follow-up spectroscopic observations revealed the sources to

* Capaccioli et al. (1989) has shown that the bimodality is preserved when the analysis is restricted to the highest quality data.

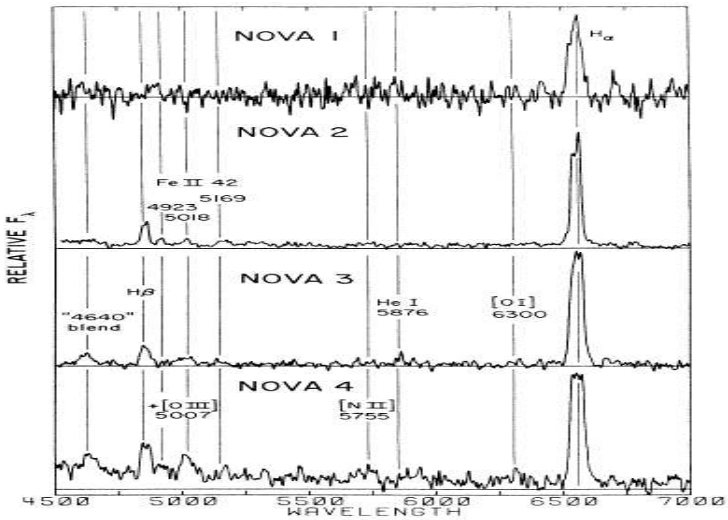

Fig. 14.2. Optical spectra of four M31 novae from Ciardullo et al. (1983) during decline from maximum light. Note the prominent Hα emission lines.

be novae during their decline from maximum light (see Figure 14.2). Although it had been known for some time that novae developed strong Hα emission shortly after maximum, the use of a nova's Hα emission as an aid to discovery, and as a potential standard candle, was not appreciated prior to this time. Not only does a nova's strong Hα emission provide increased contrast against a galaxy's background light, the fade rate is considerably slower in Hα making frequent monitoring less important than with broad-band observations. The first Hα survey of M31 was conducted during the period 1982–1986 by Ciardullo et al. (1987) using telescopes at Kitt Peak National Observatory, McDonald Observatory, and the Wise Observatory in Israel. The results of this study yielded an improved nova rate for the bulge of M31, and clearly established, contrary to the conclusions of Arp and Rosino, that the nova distribution follows the light all the way to the center of the galaxy.

Perhaps the most surprising, and controversial, result of the study concerned the extended radial distribution of novae. When the Arp (1956) sample of novae (which extended to larger galactocentric radii than the Hα observations) was included in the sample, a comparison of the radial nova distribution with model bulge and disk luminosity profiles revealed that the nova rate per unit B light in the bulge of M31 was at least an order of magnitude greater than the corresponding rate in the disk, and was formally consistent with *all* the novae arising from M31's bulge population. This result was unexpected considering that Galactic observations, although hampered by extinction, appeared to suggest that novae belonged to an old disk population (e.g. Patterson 1984, cf. Wenzel & Meinunger 1978). The association of novae primarily with M31's bulge was corroborated in a comprehensive analysis of available M31 nova data undertaken by Capaccioli et al. (1989) who estimated that $\sim 85\%$ of the novae arise in the galaxy's bulge and halo. It should be pointed out, however, that since M31 is observed at a relatively high inclination to the line of sight, it is difficult to unambiguously determine the true position of a nova from the position projected onto the sky. The difficulty in interpreting the spatial distribution of both Galactic and M31 novae has been illustrated quite effectively by the Monte Carlo simulations of Hatano et al. (1997a,b).

The possibility that the spatial distribution of novae in M31 has been biased towards bulge novae because of extinction im M31's disk is not easy to rule out. Although the use of Hα imaging provides a modest improvement over earlier studies, the Ciardullo et al. (1987) Hα bulge survey relied on B-band observations from Arp's (1956) to extend their spatial coverage. In an attempt to further explore the effect extinction in M31's disk may have on the spatial distribution of novae, Shafter & Irby (2001) extended Hα observations further out along M31's major axis and well into the disk. To assess the degree to which extinction may be biasing the novae results, they also analyzed the spatial distribution of M31's planetary nebulae (PNe), which should be at least as effected by extinction as the novae since the former were detected via their [O III]λ5007 emission. Since the stellar death rate of a system of stars (and presumably the rate of PNe formation) is not expected to be sensitive to the age, metalicity, or the initial mass function of the underlying stellar population (Renzini & Buzzoni, 1986), the radial PNe surface density profile should provide a fiducial by which to compare the radial nova density distribution. As shown in Figure 14.3, unlike the nova distribution, the planetary nebula distribution drops off more slowly with distance from the nucleus than does the bulge light, but is in good agreement with the radial distribution of the overall galaxy's background B light. Thus, regardless of the effects of extinction, the nova distribution is clearly more centrally concentrated than the PN distribution, and is consistent with an association with M31's bulge. A similar conclusion was reached by Darnley (2004, 2006) in their analysis of POINT-AGAPE microlensing data. These authors found a bulge nova rate per unit r' flux more than five times greater than that in the disk, and a surprisingly high global nova rate of 65^{+16}_{-15} yr^{-1}.

In addition to M31, the spatial distribution of novae has also been studied in another nearby spiral galaxy, M81, with conflicting results. Shara et al. (1999) analyzed 23 novae in M81 discovered on 5m Palomar plates taken in the early 1950s by a number of observers, including Humason, Sandage, Baade, Baum, Hubble, and Minkowski, and found evidence for an appreciable outer disk/spiral arm nova population. The overall spatial distribution of novae was found to be considerably more extended than the background galactic light. In a more recent and exhaustive Hα study, Neill & Shara (2004) conclude, in agreement with the M31 results, that the spatial distribution of novae in M81 follows the bulge light much better than the disk or total light. As was the case with the earlier broad-band B surveys of M31 by Arp (1956) and Rosino (1964, 1973), it is likely that the spatial distribution derived from the early Palomar data was biased by the difficulty in finding novae in the bright central regions of M81.

The surprising result that M31's nova population may be bulge-dominated, led Ciardullo et al. (1987) to speculate that the bulge nova rate may be enhanced by nova binaries that were spawned in M31's globular cluster system, and subsequently

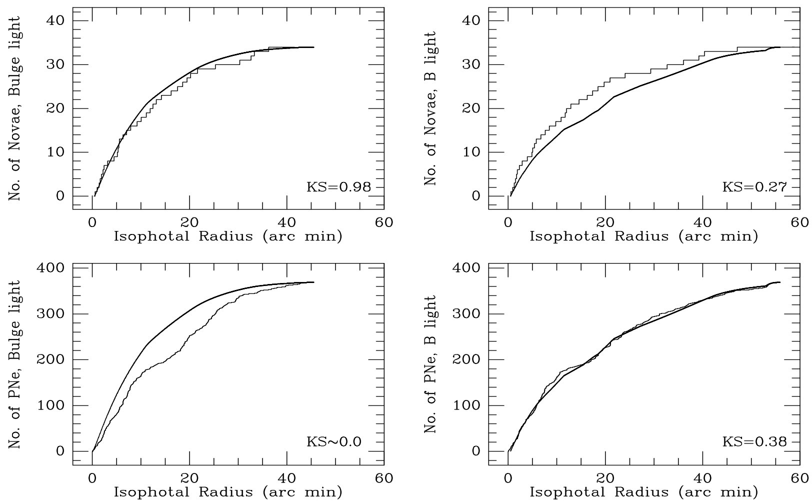

Fig. 14.3. The cumulative distributions of M31 novae and PNe are compared with the background B light and with the Bulge light. The nova distribution matches the bulge light better than the background light, while the opposite is true for the PNe. Since the PNe are discovered from their [O III]λ5007 emission, and the nova from their Hα emission, the difference cannot be due to extinction.

injected into the bulge through 3-body encounters in clusters (e.g. McMillan 1986), or by tidal disruption of entire clusters, or both. It has long been recognized that the number of X-ray sources per unit mass is of order a hundred to a thousand times higher in globular clusters compared with the rest of the Galaxy (Clark, 1975; Katz, 1975). A similar enhancement of X-ray sources are seen in M31's globular cluster population (e.g. Crampton et al. 1984; Di Stefano et al. 2002). The realization that these X-ray sources are the result of captures between neutron stars and low mass main sequence companions has led to the expectation that globular clusters should produce an even greater number of close red dwarf – white dwarf binaries, including classical novae (e.g. Hertz & Grindlay 1983; Rappaport & Di Stefano 1994). To date at least one, and likely two classical novae have been observed in the cores of Galactic globular clusters: T Sco in M80 (Luther 1860; Pogson 1860; Sawyer 1938), and an anonymous nova near the core of M14 in 1938 (Hogg & Wehlau, 1964). After initially disappointing searches, recent observations with *HST* and *Chandra* have started to reveal increasing numbers of cataclysmic variables in Galactic globular clusters (Knigge et al., 2002; Pooley et al., 2002; Heinke et al., 2003; Edmonds et al., 2003).

Attempts to directly detect novae in M31's globular cluster system have been undertaken by Ciardullo, Tamblyn & Phillips (1990), and by Tomaney (1992). Both studies make use of the fact that at maximum light, the luminosity of an average nova is comparable to the integrated luminosity of a typical globular cluster. Thus, careful photometry of M31 clusters can detect a nova eruption. In the first study, using a Fourier point-spread-function matching technique, Ciardullo et al. measured the brightnesses of 54 M31 globular clusters that fell in the fields covered by the Ciardullo et al. (1987) nova survey. Over an effective survey time of ~ 2 yr, no cluster showed a brightness increase indicative of a nova outburst, whereas Ciardullo, Tamblyn & Phillips (1990) claimed as many as three would be expected if the enhancement of novae in globular clusters were comparable to that of the X-ray sources found by Crampton et al. (1984). In a different approach, Tomaney (1992) used a multi-fiber spectrograph on the McDonald Observatory 2.7m reflector to search for novae through their expected Hα emission. A total of over 200 globular clusters were observed over an effective survey time of ~ 1 yr. The failure to detect enhanced Hα emission from any cluster led Tomaney to conclude that the enhancement of novae in M31's globular cluster system was unlikely to be as high as that of low-mass X-ray binaries.

Not all searches for novae in extragalactic globular cluster systems have been fruitless. In a recent development, Shara & Zurek (2002) have discovered a nova coincident with a globular cluster of M87. Taken at face value the detection of one nova in the 1057 globular clusters of M87 over an effective survey time of 90 days suggests a globular cluster nova rate of ~ 0.004 yr^{-1} cluster^{-1}, which is ~ 100 times more frequent than one would expect if novae are not enhanced in the clusters. Of course, it is possible (though unlikely) that the nova is a chance superposition of a field nova, or that they were just very lucky to have found this one example. Clearly, additional monitoring of extragalactic globular cluster systems, and the improved statistics that will come as a result, will be necessary to reach any definitive conclusions regarding cluster nova rates.

14.2.1 Two populations of novae?

The idea that novae from differing stellar populations may have distinct outburst characteristics finds support in theoretical studies of nova outbursts (e.g. Shara, Prialnik, & Shaviv 1980; Shara 1981; Prialnik et al. 1982; Livio 1992; Prialnik & Kovetz 1995), which have shown that the character of the outburst (e.g. peak luminosity and decline rate) depends on properties such as the white dwarf's mass, luminosity, and accretion rate, some or all of which may vary systematically with the underlying stellar population. The strength of the nova outburst is most sensitive to the mass of the accreting white dwarf. The increased surface gravity of a more massive white dwarf results in a higher pressure at the base of the accreted envelope at the time of thermonuclear runaway, resulting in a more violent outburst. In addition, since a smaller mass of accreted material is required to achieve the critical temperature and density necessary for a runaway, nova outbursts produced on massive white dwarfs are expected to have shorter recurrence times and faster light curve evolution. Population synthesis studies have shown that the mean white dwarf mass in a nova system is expected to decrease as a function of the time elapsed since the formation of the progenitor binary (de Kool, 1992; Tutukov & Yungelson, 1995; Politano, 1996). Thus, the proportion of fast and bright novae, which are associated with massive white dwarfs (Prialnik & Kovetz, 1995; Livio, 1992), might be expected to be higher in a younger stellar population. In addition, as discussed by Yungelson, Livio & Tutukov (1997), the later Hubble type galaxies, and in particular, low-mass late-type galaxies such as M33 and the Magellanic Clouds, with their younger stellar populations should be more prolific nova producers than are their earlier Hubble type counterparts.

By 1990 the possibility that there may be two distinct populations of novae with differing outburst evolution was beginning to gain significant observational support. In a study of the spatial distribution of Galactic novae, Duerbeck (1990) found that the observed number counts of novae showed an inflection point near $m = 6$ beyond which the number counts increased as expected for the contribution of a separate and more distant population. Based both on a tendency for novae in the Galactic bulge to be 'slower' in outburst development when compared to nearby disk novae, and on similar differences in speed class noted for novae in M31 and those in the LMC, Duerbeck became the first to formally postulate the existence of two populations of novae: a relatively young population that he called 'disc novae', which were found in the solar neighborhood and in the LMC, and 'bulge novae', which were concentrated towards the Galactic center and found in the bulge of M31, and were characterized by generally slower outburst development. The argument in favor of two populations of novae was further developed by Della Valle (1992), who showed that the average scale height above the Galactic plane for 'fast' novae ($t_2 < 13$ d*) is smaller than for novae with slower rates of decline. At about the same time, Williams (1992) was proposing that classical novae could be divided into two classes based on their spectral properties: specifically, the relative strengths of either their Fe II or He and N emission lines. Novae with prominent Fe II lines ('Fe II novae') usually show P Cygni absorption profiles, and tend to evolve more slowly, have lower expansion velocities, have a lower level of ionization, compared with novae that exhibit strong lines of He and N (the 'He/N novae'). In addition, the latter novae display very strong neon lines, but not the forbidden lines that are often seen in the 'Fe II' novae. Following up on their earlier work, Della Valle & Livio (1998) noted that Galactic novae with well-determined distances that were classified as 'He/N' were concentrated near the Galactic plane, and tended to be faster, and more luminous compared with their Fe II counterparts.

The available evidence in support of two nova populations from extragalactic data is mixed. Supporting evidence has been described in a series of papers by Della Valle and collaborators (Della Valle et al., 1994; Della Valle, 1995, 2002), who point out that novae in 'disk dominated' galaxies, such as the LMC, appear to be on average faster and brighter than novae arising from the bulge of M31. Available spectroscopic evidence, although limited, appears consistent with this picture. In spectroscopic observations of a total of 13 novae in the inner region of M31 (presumably from the bulge), both Ciardullo et al. (1983) and Tomaney & Shafter (1992) find no examples of the violent eruptions and high ejection velocities that are commonly observed in Galactic 'disk' novae. Only one nova observed by Tomaney & Shafter (McD89 No.1) appears consistent with classification as a He/N nova.

Not all extragalactic data, however, support the two-population scenario. Despite the bimodal maximum magnitude distribution seen in the M31 data (Arp, 1956; Capaccioli et al., 1989), there doesn't appear to be any correlation between rate of decline of M31 novae and their spatial position within the galaxy (Sharov, 1993;

* See Chapter 2 for definition of t_2

Shafter, 2002). Such a correlation should be expected in a two-population scenario given the relationship between maximum magnitude and rate of decline (see the MMRD relation in Section 14.4). Finally, a challenge to the idea of distinct nova populations has come from a recent, and pioneering effort by Ferrarese et al. (2003), who conducted the first *Hubble Space Telescope* survey specifically designed to discover novae in another galaxy. In a 55 day observing campaign targeting the Virgo elliptical NGC 4472 (M49), Ferrarese et al. discovered a total of nine novae. Perhaps the most interesting result from this study does not concern the nova rate in M49, which will be discussed in the next section, but rather the properties of the M49 nova light curves themselves. Specifically, Ferrarese et al. found that M49 appeared to lack a significant population of slow, faint novae compared with the Milky Way and M31. Instead, they found that the decline rates were remarkably similar to the faster novae in the LMC (see Figure 14.4).

Despite the intriguing nature of these findings, there are a few caveats to be considered. Since only a relatively small number of nova light curves were available in the study, the light curve properties may not be representative of the global M49 nova population. Another potential concern is that the stellar population of M49 and other radio-loud ellipticals may be contaminated through mergers with late-type galaxies. In particular, Della Valle & Panagia (2003) have shown that radio-loud elliptical galaxies exhibit an overproduction of Type Ia supernovae, which they speculate may result from contamination by a ~ 1 Gyr stellar population. Since some fraction of Type Ia supernova progenitors may be related to the cataclysmic variables, recurrent novae, in particular (e.g. see Livio 2000), it is possible that the nova rate in radio-loud ellipticals may also be enhanced by the mergers (see Chapter 3 for a discussion of this point). If so, it would not be surprising if properties of the nova population in these systems showed similarities to those of late-type galaxies.

14.3 Extragalactic nova rates

By the early 1990s novae had been detected in a total of eight extragalactic systems, in six with sufficient numbers for an estimate of their nova rates. The first study comparing nova rates in a broad range of galaxies was that of Ciardullo et al. (1990a) who compared the nova rate in NGC 5128 with those in the SMC, LMC, M31, M33, and a sample of Virgo ellipticals. In order to compare nova rates in different galaxies, it is necessary to normalize the rates by the stellar mass surveyed. Because novae arise from an evolved stellar population, Ciardullo et al. chose to normalize the nova rates by the galaxy's infrared K magnitude, which they adopted as a convenient proxy for the mass in evolved stars. The resulting normalized nova rates are referred to as Luminosity-Specific Nova Rates (LSNRs). When comparing LSNRs, Ciardullo et al. found no evidence for a systematic variation with the Hubble type of the galaxy (see Figure 14.5), although the error bars for the individual galaxies were quite large.

A few years after the publication of the Ciardullo et al. (1990a) analysis, a similar study was published by Della Valle et al. (1994), who came to very different conclusions regarding the variation of the LSNR with the Hubble type of the galaxy. Despite the considerable overlap in the galaxies studied (Della Valle et al. included a recent estimate of the nova rate in M81, while excluding the poorly known nova rate estimate for the SMC), the latter authors found that early type galaxies, specifically

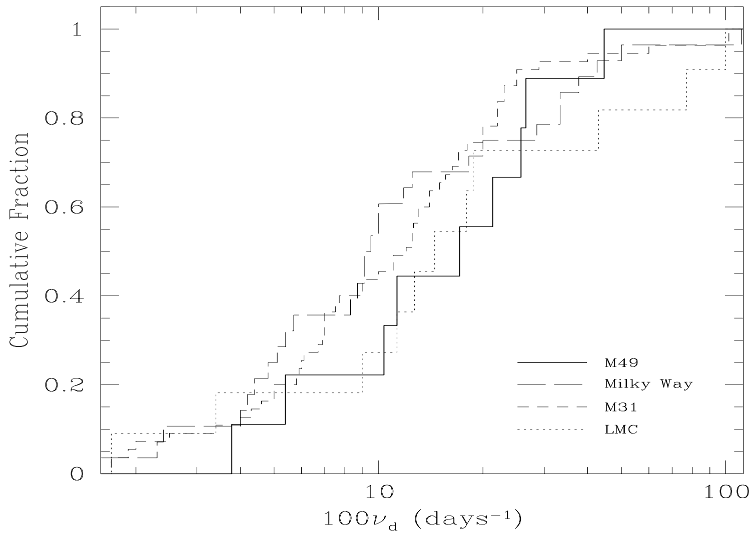

Fig. 14.4. The cumulative distribution of novae as a function of fade rate for several galaxies (from Ferrarese et al. 2003). Note that the fade rate distribution of the M49 novae matches that of the LMC better than those of M31 and the Galaxy.

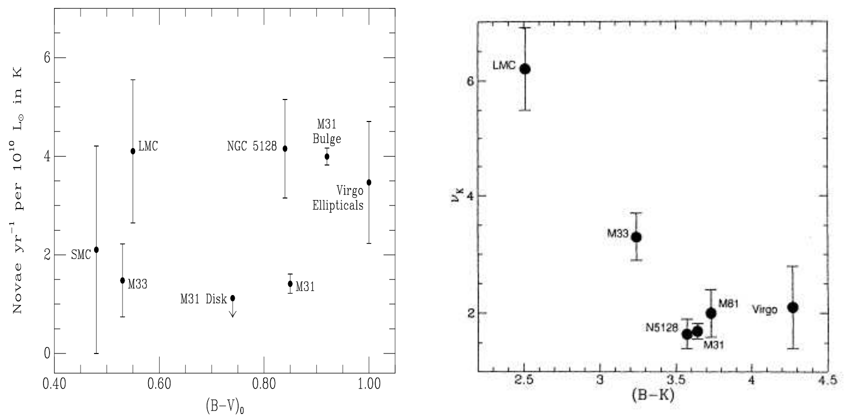

Fig. 14.5. LSNRs plotted as a function of galaxy color. Ciardullo et al. (1990a) find no dependence with galaxy type (left panel), while Della Valle et al. (1994). find that late type galaxies are more prolific nova producers (right panel).

the LMC and M33, were more prolific nova producers, with LSNRs that were roughly a factor of three greater than their earlier type counterparts (see Figure 14.5). The population synthesis models of Yungelson, Livio & Tutukov (1997), published a few years later, which showed that nova rates should be enhanced in galaxies with active star formation, appeared to provide a theoretical foundation to the observational results of the Della Valle et al. study.

14.3.1 Determining the LSNR

The determination of the LSNR of a galaxy involves several steps, and represents a challenging observational task. Broadly speaking, the procedure can be divided into two principal tasks: estimating the nova rate, usually in a limited region of the galaxy, and estimating the infrared luminosity in this surveyed region. Regardless of galaxy type, uncertainty in the nova rate arises because of difficulty in characterizing the extent of incompleteness in the nova surveys. As a result of practical restrictions on telescope availability, most surveys have been synoptic in nature and have relied on estimates of the length of time the average nova remains detectable to compute nova rates. Since the absolute magnitude of novae at maximum light and their rate of decline are variable, and are likely to depend on stellar population, a determination of nova detectability is problematic. Generally, two approaches have been employed: a mean nova lifetime approach, and a Monte Carlo approach. In both cases a representative sample of nova light curves is needed, and the requisite mean nova lifetime relations have been calibrated from an assumed absolute nova rate in the bulge of M31 (e.g. Capaccioli et al. 1989 for broad-band B data; Ciardullo et al. 1990b for Hα data).

The mean lifetime approach, employed by both Ciardullo et al. (1990b) and Della Valle et al. (1994), is based on a procedure first used by Zwicky (1942) to study the frequency of supernovae. For a total of $N(M < M_{\rm lim})$ novae observed brighter than a survey's limiting absolute magnitude $M_{\rm lim}$, the nova rate is given by

$$\mathcal{R} = \frac{N(M < M_{\rm lim})}{T(M < M_{\rm lim})}, \tag{14.1}$$

where $T(M < M_{\rm lim})$ – the total number of days the survey is able to detect an average nova – is known as the effective survey time. If, following Ciardullo et al. (1990b), $\tau_{\rm lim}$ is defined to be the mean nova lifetime (the length of time in days an average nova remains brighter than the limiting magnitude of the survey), then for multi-epoch observations, the effective survey time is given by

$$T(M < M_{\rm lim}) = \tau_{\rm lim} + \sum_{i=2}^{n} \min\,(t_i - t_{i-1}, \tau_{\rm lim}), \tag{14.2}$$

where t_i is the time of the i$^{\rm th}$ epoch of observation. If $\tau_{\rm lim}(M_{\rm lim})$ is known, $\mathcal{R}$ can be calculated directly from the nova observations and a knowledge of the galaxy's distance. Based on an annual nova rate of 23.2 ± 4 yr^{-1} in M31's bulge (Capaccioli et al., 1989), and Hα light curve data for 40 M31 bulge novae observed over a seven year period, Ciardullo et al. (1990b) estimated $\log\ \tau_{\rm lim} \simeq 5.6 + 0.48 M_{\rm lim}$ over the typical range of nova luminosities. If additional Hα light curve data from the M31 study of Shafter & Irby (2001) are included, the second-order relationship:

$$\log\ \tau_{\rm lim} \simeq -4.78 - 2.10 M_{\rm lim} - 0.162 M_{\rm lim}^2, \tag{14.3}$$

shown in Figure 14.6, provides a slightly better fit to the data.

The mean nova lifetime approach followed by Della Valle et al. (1994) is similar, and relies on the B band light curves of the nova sample given in Capaccioli et al. (1989). In either case, the reliability of the mean nova lifetime method relies both

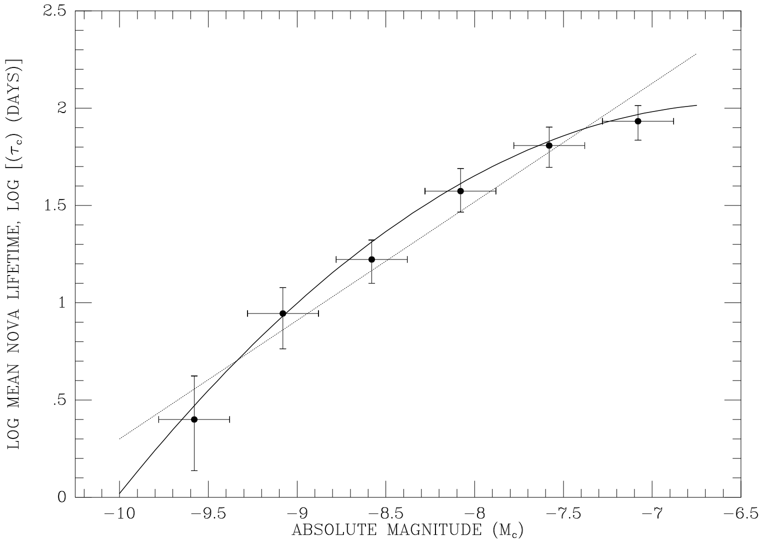

Fig. 14.6. The Hα mean nova lifetime relation for a sample of 64 M31 novae from Shafter & Irby (2001). The mean nova lifetime is an estimate of the average number of days a nova remains brighter than a specified absolute magnitude in Hα. The solid curve is the best second-order fit to the data, as given by equation (14.3).

on an accurate knowledge of M31's bulge nova rate, and on the assumption that the light curve properties of the M31 nova sample is representative of novae in the galaxy being studied. Since the M31's bulge rate may be in error, and the properties of the bulge novae may not be characteristic of novae from disk populations, nova rates computed using the mean nova lifetime approach should be viewed with appropriate caution.

A better approach for estimating extragalactic nova rates involves the use of numerical simulations, which do not depend on a knowledge of the absolute nova rate in M31's bulge. Here, for a given assumed global nova rate, $\mathcal{R}$, a model population of novae at various stages in their outburst evolution is produced using a sample of known light curve properties (e.g. from the M31 bulge sample) and compared with number of novae observed, $N_{\rm nova}$. The number of novae detectable will depend on the frequency of observation and the limiting absolute magnitude of the survey. The completeness as a function of magnitude over the surveyed region, $C(m)$, can be estimated from artificial star tests and then convolved with the model nova luminosity function, $N(m, \mathcal{R})$, to predict the number of novae detected in the survey (e.g. Williams & Shafter 2004):

$$N_{\rm obs}(\mathcal{R}) = \int C(m) * N(m, \mathcal{R})\; dm. \qquad (14.4)$$

The nova rate is given by the value of $\mathcal{R}$ that produces the best match between $N_{\rm obs}(\mathcal{R})$ and $N_{\rm nova}$.

Both the mean nova lifetime and Monte Carlo approaches have a principal drawback: The currently available light curve data, which are derived mainly from novae in the bulge of M31, may not accurately reflect the distribution of decline rates in different galaxies. If, for example, the novae in the target galaxy are generally faster than those from M31's bulge, then the nova lifetime will be overestimated, and the rate underestimated. To guard against this possibility, Neill & Shara (2004) in their recent study of novae in M81 have stressed the need for near continuous coverage in extragalactic surveys to make sure that the fastest novae are not overlooked. Clearly, continuous coverage will reduce the uncertainty in the nova rate calculations, and should be used when feasible. The only concern is that the limiting magnitude of the survey goes sufficiently deep to assure that the slower (and less luminous) novae are not missed. If only the brightest novae are observed, even a continuous coverage survey will depend on the distribution of speed class within the target galaxy.

Over the past decade, LSNRs have been determined for several additional galaxies. In an attempt to better constrain the LSNRs in late-type galaxies Shafter, Ciardullo & Pritchet (2000) initiated a nova survey of the spiral galaxies NGC 5194/5 (M51) and NGC 5457 (M101). For comparison, the early-type giant elliptical galaxy, NGC 4486 (M87), was also monitored. Although the results of this program found that the LSNRs in the spiral galaxies were somewhat lower than that of M87, within the errors of measurement, the differences were not significant. Overall, the conclusions of Shafter et al. were consistent with those of Ciardullo et al. (1990a), namely there was no compelling evidence that the LSNR varied systematically with the Hubble of the galaxy. In their *HST* study of novae in the Virgo elliptical M49, Ferrarese et al. (2003) found an LSNR virtually identical with that found by Shafter et al. for M87. Upon considering the full sample of galaxies with measured nova rates Ferrarese et al. conclude that the LSNR in M49 is fully consistent with that measured in all other galaxies for which data are available, with the possible exception of the LMC.

A comparison of LSNRs among galaxies is given in Williams & Shafter (2004), who have completed a multi-epoch survey of M33 in an attempt to reconcile the large discrepancy between published nova rates for this galaxy. Their revised M33 nova rate of 2.5 yr^{-1} yields a LSNR that is consistent with those of most other galaxies. Specifically, they find that the LSNR is constant across a wide range of Hubble types at a value of $\sim 2 \times 10^{-10}$ yr^{-1} $L_{K,\odot}^{-1}$, with the exceptions of the Magellanic Clouds, where the authors conclude that the LSNRs for these two galaxies appears to be roughly a factor of three higher (see Figure 14.7). The SMC now joins the LMC as a high LSNR galaxy as a result of an upward revision of its nova rate from the hitherto poorly determined value of 0.3 ± 0.2 yr^{-1} (Graham, 1979) to a value of 0.7 ± 0.2 yr^{-1} (Della Valle, 2002). The higher SMC rate results from the inclusion of recent nova discoveries made possible through microlensing surveys of the Magellanic Clouds.

Two other studies have found relatively high LSNRs in early-type galaxies. In a preliminary study of *HST* archival images, Shara & Zurek (2002) have reported the discovery of over 400 classical nova candidates in M87, leading to an estimated annual nova rate of at least 300 yr^{-1}. Subsequently, Neill & Shara (2005) have made preliminary estimates of the LSNRs in the local group dwarf ellipticals M32 and NGC205 that are the highest measured for any galaxy. If these results are confirmed, it will necessitate a radical reassessment of the current ideas regarding nova rates in differing stellar populations (e.g. Yungelson, Livio & Tutukov 1997 and Chapter 3). The galactic chemical evolution models of Matteucci et al. (2003) may provide a step in that direction, as they predict nova rates should scale closely with

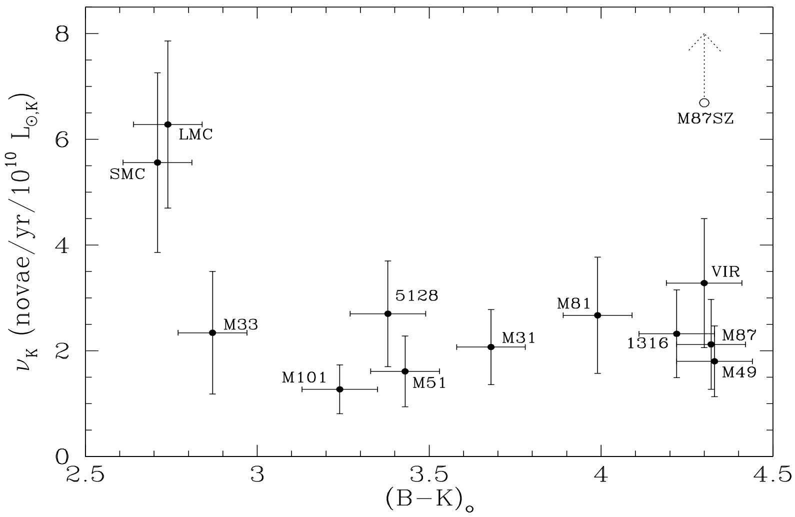

Fig. 14.7. The LSNR plotted as a function of galaxy color from the recent study of Williams & Shafter (2004). All galaxies appear to have similar LSNRs with the exceptions of the Magellanic Clouds and possibly M87. The M87SZ point is based on the Shara & Zurek (2002) nova rate.

galaxy mass, with little dependence of the LSNR on stellar population. Thus, giant elliptical galaxies such as M87 are predicted to have particularly high nova rates. Despite the difference between the predictions of Yungelson et al. and Matteucci et al., it is clear that all attempts to model Galactic nova rates must depend on input parameters such as the fraction of white dwarfs that end up in nova binaries, the time delay from zero-age main sequence to nova production, and the recurrence time between nova outbursts (see Chapter 3 for detailed discussion), all of which are uncertain and are likely to vary with galaxy morphology.

14.3.2 Uncertainties in the LSNRs

A major source of uncertainty in the global nova rates concerns the role of extinction in shielding an unknown number of novae from detection and in hampering an accurate estimate of galaxy luminosity. Clearly, this uncertainty is much more of a concern in the dusty environments of irregular galaxies and the disks of spirals, where the optical depth may be higher than usually assumed (Disney et al., 1989). Although the use of Hα imaging in these late-type galaxies can minimize the impact of extinction, we are unlikely to fully understand the extent of the problem until nova surveys in the near infrared have been conducted. Advances in large-format IR imaging detectors has now made such surveys feasible. In the near infrared, a possible alternative to Hα imaging would be to image in O I λ8446Å, which has been observed to be strongly in emission in erupting novae (e.g. Strittmatter et al. 1977).

In cases where the entire galaxy is not surveyed, uncertainty in the global nova rate is also introduced during the process of extrapolating the measured nova rate to the entire galaxy from a comparison of the light sampled in the survey with that of the galaxy as a whole. Not only is an estimate of the luminosity sampled in spiral systems complicated by patchy extinction and numerous H II regions, the extrapolations implicitly assume that the LSNR is constant throughout the galaxy, which, given the radial population gradient, it may well not be. Generally, determining the LSNR in elliptical galaxies, which contain little dust and a nearly homogeneous stellar population, is relatively straightforward compared with dusty, multi-population spiral systems where identification of the stellar population of the nova progenitors is a problem.

Finally, the computation of a LSNR requires a measurement of the infrared luminosity of the galaxy. Until recently only B magnitudes were available for many galaxies and estimates of $(B-K)$ color were necessary to convert available photometry to the infrared magnitudes required to compute the LSNRs. Often the $(B-K)$ color of a galaxy was either poorly known, or was measured from aperture photometry for the inner region of the galaxy only. That situation has changed recently with the publication of the 2MASS catalog, which contains K-band data for nearby, large-angular-size galaxies. Unfortunately, as noted by Williams & Shafter (2004) in their study of novae in M33, the published 2MASS K-band magnitudes of nearby, large angular diameter galaxies are subject to large errors due to difficulty in background subtraction. Future infrared studies should not only resolve this discrepancy, but should aid in the detection of novae in the dusty regions of late-type galaxies.

14.4 Novae as distance indicators

Given both their high outburst luminosities ($-7 > M_V > -9$), which make them among the most luminous objects in the cosmos, and their frequent outbursts (30 yr^{-1} in a typical spiral galaxy like the Milky Way [Shafter 2002]), novae are of obvious interest as extragalactic distance indicators (de Vaucouleurs, 1978; van den Bergh, 1981; van den Bergh & Pritchet, 1986; Jackoby et al., 1992; Livio, 1992; Della Valle & Livio, 1995; Livio, 1997; Gilmozzi & Della Valle, 2003). In addition to being up to ~ 2 mag brighter on average than the longest period Cepheid variables, novae are found in both Population I and Population II environments. Thus, they are found in elliptical galaxies, and in uncrowded, dust-free regions of spiral galaxies where Cepheids, for example, do not exist (van den Bergh, 1981).

As discussed previously, the principal obstacle in the early years to the use of novae as distance indicators concerned their large dispersion in absolute magnitude, which was particularly acute until the distinction between novae and supernovae was finally appreciated in the 1930s. However, as the observations of novae in M31 by Hubble (1929) had shown, there was still a considerable spread of order 3 magnitudes in luminosity, even with the exclusion of supernovae. Although Hubble had pointed out that bright novae in M31 faded faster than faint novae, the real breakthrough came when McLaughlin (1945) calibrated a relationship between a nova's luminosity and its rate of decline, which he referred to as the 'life-luminosity relation'*. This relation, which became widely known in subsequent years as the Maximum Magnitude – Rate of Decline, or MMRD, relation is usually cast in a form with the absolute magnitude given as a linear function of $\log t_n$, where, as usual, t_n is the time in days a nova takes

* Zwicky (1936) is often given credit for being the first to discover the 'life-luminosity' relation for novae; however, Zwicky's analysis, which failed to distinguish between novae and supernovae, led to the misimpression that bright novae faded more slowly than their fainter counterparts.

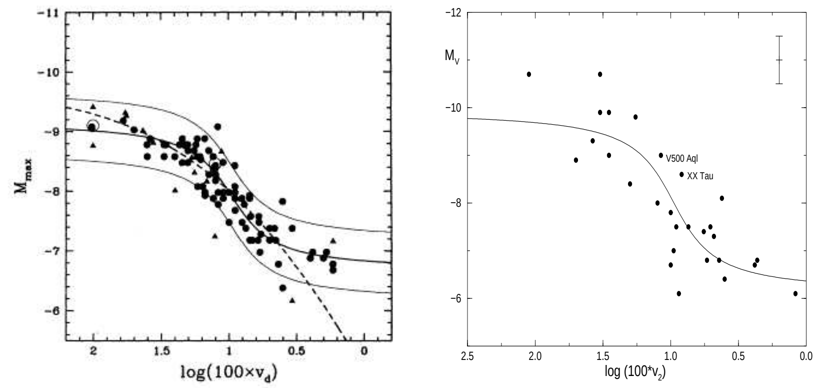

Fig. 14.8. MMRD relationship!novae in M31 novae (left panel, from Della Valle & Livio (1995) and for Galactic novae (right panel, from Downes & Duerbeck (2000)). The 'S'-shaped curves are empirical fits of the form given in equation 14.5. The dashed line represents a theoretical relation from Livio (1992).

to decline n magnitudes from maximum light (usually $n = 2$ or 3). The relation has been calibrated for Galactic novae numerous times over the years (Kopylov, 1952, 1955; Schmidt-Kaler, 1957; Pfau, 1976; de Vaucouleurs, 1978; Duerbeck, 1981; Cohen, 1985; Downes & Duerbeck, 2000); further discussion of these relationships may be found in Chapter 2.

Much of the scatter in the Galactic MMRD relation, which is caused by difficulty in measuring accurate distances to novae, can be minimized by observing a nearly equidistant sample of novae in nearby galaxies such as M31 and the Magellanic clouds. Although the linear MMRD relations provide acceptable fits for Galactic novae, more complicated empirical relations have been proposed in recent years to improve the fit when extragalactic data are included. One such calibration for novae in M31 and the LMC is given by Della Valle & Livio (1995):

$$M_V = -7.92 - 0.81 \text{ arctan} \frac{1.32 - \log\ t_2}{0.23}, \tag{14.5}$$

and is shown graphically in Figure 14.8. The flattening at the bright end of the relation is expected from theoretical modeling of the nova eruption Livio (1992), and is the result of the white dwarf mass approaching the Chandrashekhar limit. The reality of the flattening at the faint end has been questioned by Warner (1995), and may be due to observational bias. For comparison, data for Galactic novae (Downes & Duerbeck, 2000) are shown in Figure 14.8 and compared with a similar relation. As expected the scatter in the Galactic data is somewhat larger, and the data can be fit just as well by a linear relation (not shown, but cf.):

$$M_V = -(11.32 \pm 0.44) + (2.55 \pm 0.32)\ \log t_2. \tag{14.6}$$

In addition to the MMRD relation, there have been numerous additional techniques developed that allow novae to be employed in the determination of extragalactic distances. As discussed in Chapter 2 (cf. Table 2.4), another calibration of nova

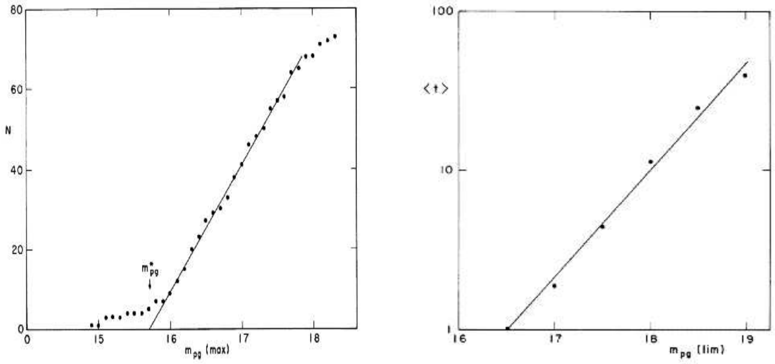

Fig. 14.9. Left Panel: The cumulative broad-band blue luminosity distribution of M31 novae at maximum light from van den Bergh & Pritchet (1986), who proposed that extrapolation of the linear portion of the distribution, '$m^*_{\rm pg}$', could be used as a standard candle. Right Panel: The mean period of visibility of M31 novae is plotted as a function of limiting magnitude (also from van den Bergh & Pritchet 1986). The linear regression line is given by equation (14.7).

magnitudes was proposed by Buscombe & de Vaucouleurs (1955), who reasoned that if fast novae faded more rapidly than slow novae, their light curves must intersect. Based on a sample of well observed Galactic nova light curves, they found that at approximately 15 days after maximum light the absolute visual magnitude of novae was given by $\langle M_{15}\rangle = -5.2 \pm 0.1$ (p.e.) irrespective of speed class. Like the MMRD relation, there have been various attempts to better calibrate this quantity (e.g. Capaccioli et al. 1989; Ferrarese et al. 2003; Downes & Duerbeck 2000), but it is generally not considered as reliable as the MMRD relation.

The potential of using novae for measuring extragalactic distances was further developed by van den Bergh & Pritchet (1986), who pointed out that quantities derived from the nova luminosity function could also be used in lieu of the MMRD relation. Based on the Arp (1956) and Rosino (1964, 1973) M31 nova samples, van den Bergh & Pritchet proposed extrapolating the linear portion of the broad-band blue integrated luminosity function of the magnitudes at maximum light to obtain the quantity '$m^*_{\rm pg}$', which they proposed as a 'standard candle' (see Figure 14.9). Unfortunately, this technique will not work for Hα data. As shown by the M31 observations of Ciardullo et al. (1990b), the Hα luminosity function of novae is a power law, and cannot be used to measure distances. Furthermore, the fade rate of a nova's Hα emission is not well correlated with its Hα flux at maximum light; thus, there appears to be no useful Hα MMRD relation either.

In another technique, van den Bergh & Pritchet argued that the mean period of nova visibility, as calibrated by Arp's M31 sample, could also be employed as a distance indicator. In particular, they found that the M31 data were well-represented by the relation:

$$\log \langle t \rangle = 0.67\, m_{\rm pg}({\rm lim}) - 11.0, \tag{14.7}$$

which shows that the period that a nova remains visible depends critically on the limiting magnitude of the survey (see Figure 14.9). Although promising, both of these have significant drawbacks that have curtailed their use. Firstly, both techniques implicitly assume that the relative frequency of novae with differing rates of decline is constant from galaxy-to-galaxy, which may not be the case. Secondly, a practical difficulty arises since both techniques rely on properties of the nova luminosity function, a large sample of complete nova light curves must be obtained. The MMRD relation is more robust in that a large sample of nova light curves (although desirable) is not required, and in that it is insensitive to the relative proportion of fast and slow novae. All that is required is that the relation itself be universal.

14.4.1 Recent developments

Despite their virtues, the use of novae as distance indicators has not become particularly widespread. As just discussed, a major impediment has been the severe impositions on telescope time required to characterize nova light curves and determine fade rates used to calibrate the luminosity. Since the magnitude at maximum light must be observed, densely spaced monitoring programs must be in place to discover and follow novae over many consecutive weeks. In addition to these practical hurdles, the nagging questions about the putative effect of stellar population on nova properties, and thus on the universality of the MMRD relation, has dampened interest in using novae for distance measurements.

Although local group galaxies such as the LMC, M31, and M33 have been primarily used to calibrate the MMRD relation as discussed earlier, distances to these galaxies have also been determined through the use of MMRD relations calibrated in the Galaxy (Capaccioli et al., 1989, 1990). Practical challenges notwithstanding, a few notable efforts to derive extragalactic distances have been undertaken. Perhaps the most ambitious was that carried out by Pritchet & van den Bergh (1987) in their study of novae in three Virgo cluster elliptical galaxies, NGC 4365, NGC 4472 (M49), and NGC 4649 (M60). During observations that spanned 15 nights over a roughly one month period, Pritchet & van den Bergh were able to identify a total of nine novae (eight of which were in M49). The coverage was sufficient to estimate light curve properties (maximum magnitude and rate of decline) for six of these novae. A comparison with the MMRD data from the Arp (1956) and Rosino (1964, 1973) sample of novae, shown in Figure 14.10, yields a relative distance modulus between M31 and M49*, $\Delta(m - M)_B = 6.8 \pm 0.43$.

As a check, Pritchet & van den Bergh employed the 'nova visibility' technique described earlier, noting that the mean period during which seven of their reasonably well-observed novae remained brighter than $m_B = 25.0$ was 17.1 days. Substituting this value into equation (14.7) above yields $\Delta(m - M)_B = 6.74$ mag, in good agreement with the value derived from the MMRD relation. Adopting the currently accepted value for the M31 distance modulus of 24.48 ± 0.05 (Freedman et al., 2001), yields a Virgo distance modulus, $(m - M)_{\rm Virgo} = 31.28 \pm 0.40$. Although, this value is ~ 0.2 magnitude fainter than the currently accepted M49 distance of $(m - M)_{\rm M49} = 31.07 \pm 0.08$ (Ferrarese et al., 2003), the agreement is noteworthy

* This value includes the 0.2 ± 0.1 correction found by the authors in their numerical simulations of sampling biases.

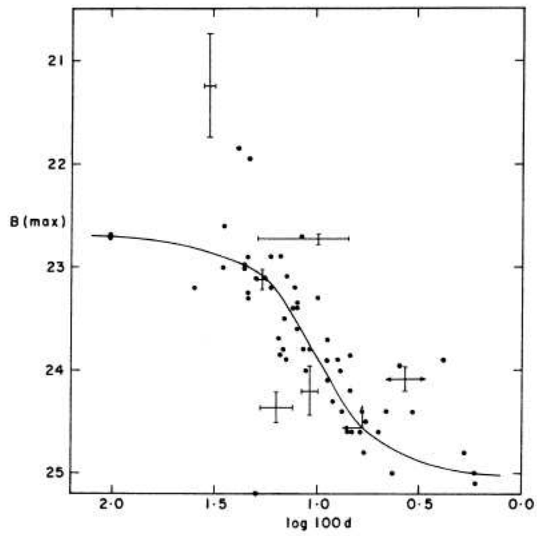

Fig. 14.10. The MMRD relation for six Virgo novae compared with the combined Arp (1956) and Rosino (1964, 1973) samples of M31 novae (from Pritchet & van den Bergh 1987).

given the relatively small number of nova light curves available in the Pritchet & van den Bergh study.

Other than the Virgo study, attempts to use the MMRD relation or the nova visibility technique to determine distances beyond the local group have been relatively few, and when employed have been based on small samples of novae. Della Valle (1988) compared the period of nova visibility in M31 with that of five novae in M33 to estimate that the latter galaxy is ~ 0.3 mag more distant than the former. A distance modulus of $(m-M)_0 = 31.0 \pm 0.3$ to M100 was obtained by Ferrarese et al. (1996) through observations of the light curve of a single nova, and has the distinction of being the first nova-based distance derived from *HST* data. More recently, Shara et al. (1999) identified one nova out of the 23 discovered in the Palomar 5m survey of M81 described earlier that had sufficient coverage for its maximum magnitude and rate of decline to be well determined. Analysis of this single nova using a (theoretically-calibrated) MMRD relation from Shara (1981) yielded a distance modulus, $(m-M)_0 = 27.75$ mag for M81. An independent distance estimate was obtained using all 23 novae through a simple comparison of their apparent magnitude at discovery distribution with that for M31 novae from the survey of Ciardullo et al. (1987). The result was a differential modulus, $\Delta(m-M) = 3.4 \pm 0.3$ mag, which coupled with the Freedman et al. (2001) M31 modulus (24.48 ± 0.05) and an estimated extinction of 0.1 mag (Sandage & Tammann, 1987) yields $(m-M)_0 = 27.8 \pm 0.3$. This value is in excellent agreement not only with the MMRD value given above, but with the recent Cepheid-based distance to M81, $(m-M)_0 = 27.8 \pm 0.08$, reported in Freedman et al. (2001).

Although the observations from the Ferrarese et al. (2003) *HST* nova study were not used by the authors to derive an independent distance to M49, they did compare the light curve properties of their M49 novae with both existing Galactic and M31 MMRD relations, finding only 'marginal agreement'. In addition, they used the M49 light curve data to recalibrate the Buscombe-de Vaucouleurs parameter, finding a value of $M_{V,15} = -6.36 \pm 0.19$, which is substantially brighter than that found from most earlier Galactic nova calibrations. In particular, it is inconsistent with the van den Bergh & Younger (1987) determination of $M_{V,15} = -5.23 \pm 0.16$, marginally consistent with both Cohen's (1985) value of $M_{V,15} = -5.60 \pm 0.45$ and Capaccioli et al.'s (1989) value of $M_{V,15} = -5.59 \pm 0.42$, but in reasonable agreement with the determination of $M_{V,15} = -6.05 \pm 0.44$ found by Downes & Duerbeck (2000). Ferrarese et al. conclude their M49 study on a pessimistic note vis-a-vis the use of novae as extragalactic distance indicators. They argue, given the observed scatter in the MMRD and M_{15} calibrations, and the practical difficulties associated with acquiring sufficient numbers of high-quality light curves, that both the surface brightness fluctuation method (Tonry et al., 2001) and potentially the globular cluster luminosity function both offer more effective methods for determining distances to Population II galaxies.

A more optimistic view is provided by the work of Della Valle and collaborators, who have touted the use of 10-m class telescopes to significantly improve the efficiency of nova detections in galaxies beyond the Local Group. In a pilot program designed to test the improvements in nova detection efficiency made possible with the latest generation of large optical telescopes, Della Valle & Gilmozzi (2002) used the *Very Large Telescope* (*VLT*) to detect four novae in NGC 1316 (Fornax A) during nine nights between December 1999 and January 2000. Although the *VLT* observations were not dense enough to permit a distance determination through the MMRD relation, Della Valle & Gilmozzi were able to employ the M_{15} method to constrain the distance modulus of the galaxy to $31.3 \pm 0.25 < (m - M)_0 < 31.5 \pm 0.25$. NGC 1316 now holds the record as the most remote galaxy whose distance has been estimated through observations of classical novae.

As is the case with many other approaches, a potential concern when using novae to measure extragalactic distances involves the Malmquist (1922) bias. In a magnitude-limited sample of novae in a distant galaxy, only the most luminous novae will be observed. This bias appears to pose a particular problem for novae, as the existence of a class of *super-bright* novae, which are are not well characterized by the MMRD relation, has been noted by several authors (van den Bergh & Pritchet, 1986; Della Valle, 1991; Shara & Zurek, 2002). The existence of this bright nova population is readily revealed as a bright tail in the integrated nova luminosity function of M31 (see Figure 14.9). It is clear that any attempt to use novae for measuring extragalactic distances should make sure that the observations extend sufficiently far down the luminosity function to properly characterize the MMRD relation.

14.5 Directions for future studies

Despite the promise (or lack thereof) of using novae as extragalactic distance indicators, recent years have seen the emphasis of extragalactic novae studies shift from the use of novae as distance indicators to the prospect of using novae to probe the evolution of interacting close binary stars in differing stellar populations. In this context, it is the study of the aggregate properties of novae from galaxies with differing stellar populations that has taken center stage. Indeed, the central question that must be answered before meaningful progress can be made in our understanding of extragalactic novae concerns the question of whether the nova rate and the distribution of speed classes depend on stellar population. An understanding of the speed class distribution is perhaps more fundamental since the computation of nova rates typically depends on a knowledge of the mean light curve properties in the galaxy under study. Current understanding of variations in speed class between different stellar populations, which comes primarily from the samples of light curves from the LMC and the bulge of M31, needs to be improved. Not only would a larger sample of light curves improve the situation, an extensive sample of light curves from a purely population II environment would be helpful, since the sample of novae attributed to the bulge of M31 are contaminated by an unknown number of disk novae projected onto M31's bulge (Hatano et al., 1997a,b). An ideal target would be one of the massive elliptical galaxies in Virgo such as M49 or M87, which have high absolute nova rates. In view of the potential effect of galaxy mergers discussed earlier (Della Valle & Panagia, 2003), and the possible role of M87's jet in enhancing the nova rate Livio et al. (2002), it would useful to include other radio quiet Virgo ellipticals as well. A larger sample of Population I light curves should become available as by-products of various microlensing surveys toward the Magellanic Clouds in the MACHO and EROS2 surveys (Alcock, 2000; Lasserre, 2002), and toward M31 in the POINT-AGAPE survey (Darnley, 2004, 2006).

Once variations in the speed class distribution between galaxies is better understood, not only will measurements of absolute nova rates become more reliable, it will be possible to explore observationally the effect the metallicity of the accreted material has on the nova outburst, and to test the universality of the MMRD relation. Until recently the consensus has been that, for a given white dwarf mass, the properties of the eruption were expected to be relatively insensitive to the metallicity of the accreted material (e.g. Livio & Truran 1994). However, calculations by (Starrfield et al., 2000, see also Chapter 4) have shown that increasing the opacity of the accreted material will reduce the amount of material accreted prior to the thermonuclear runaway, presumably leading to a 'faster' nova. At this juncture there are reasons to expect that the MMRD relation will be shown to be universal. As pointed out by Gilmozzi & Della Valle (2003), although an older stellar population (characterized by nova binaries having a lower mean white dwarf mass) may produce generally fainter novae that erupt less frequently compared with a young stellar population, the zero-point of the MMRD relation should not be affected. The only difference between nova properties should be the relative proportion of fast (bright) and slow (faint) novae.

Finally, the question of whether the LSNR depends on the underlying stellar population will require improved confidence in the completeness of the surveys. Clearly, if past surveys have missed a significant fraction of novae either through problems with extinction in the spiral and irregular systems, or through overlooking a population of fast novae in surveys with poor temporal sampling, or both, then any conclusions regarding extragalactic nova rates, and how they may or may not depend on stellar population will be suspect. Continuous-coverage surveys, like that carried out for M81 by Neill & Shara (2004), will ensure that unusually fast novae are not missed.

However, the problem of extinction in the dusty environments encountered in spiral and irregular systems is likely to remain a problem in perhaps all but the deepest surveys. Future infrared imaging surveys offer a promising step forward in this regard. At present, however, the question of whether the rate of nova production varies with stellar population, and hence the Hubble type of the galaxy, remains unclear.

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