NEW INSIGHT INTO THE SPATIAL DISTRIBUTION OF NOVAE IN M31
KAZUHITO HATANO, DAVID BRANCH, AND ADAM FISHER
Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019

AND

SUMNER STARRFIELD
Department of Physics and Astronomy, Arizona State University, Tempe, AZ 85287
Received 1997 March 28; accepted 1997 July 11

ABSTRACT
We use a Monte Carlo technique together with a simple model for the distribution of dust in M31 to investigate the observability and spatial distribution of classical novae in M31. By comparing our model positions of novae to the observed positions, we conclude that most M31 novae come from the disk population, rather than from the bulge population as has been thought. Our results indicate that the M31 bulge-to-disk nova ratio is as low as, or lower than, the M31 bulge-to-disk mass ratio.

Subject headings: dust, extinction — galaxies: individual (M31) — novae, cataclysmic variables

1. INTRODUCTION
Opinions about the spatial distribution of classical novae in M31 and in our Galaxy have been undergoing an interesting evolution. The major searches for novae in M31 (Hubble 1929; Arp 1956; Rosino 1964, 1973; Rosino et al. 1989) showed that in a general sense novae are distributed like the light of the galaxy. Ciardullo et al. (1987) and Capaccioli et al. (1989) concluded that novae in M31 belong overwhelmingly to the bulge population. By analogy, it is often assumed that Galactic novae also come mainly from the bulge; for example, Della Valle & Duerbeck (1993) and Della Valle & Livio (1994) assume that three-fourths of the Galactic novae are from the bulge.

Doubts about the bulge dominance of the M31 nova population arose when Ciardullo et al. (1990) combined the results of their search for novae in NGC 5128 with data on novae in the LMC, SMC, M33, M31, and a few elliptical galaxies in the Virgo cluster. They found the nova rates per unit K-band luminosity to be remarkably similar—apart from a strikingly low rate for the M31 disk. They suggested that since the M31 bulge has been more thoroughly searched for novae than its disk and since disk novae may be preferentially obscured by dust, it is possible that the nova rate in the M31 disk had been underestimated and that the nova rate per unit mass of old stellar population may be approximately constant. Recently, Shafter, Ciardullo, & Pritchet (1996) report that their search for novae in three more galaxies, M51, M101, and M87, has produced preliminary results that are consistent with this proposition.

Another point of view that has developed recently is that young populations are better than old populations at producing novae. On the basis of observation, Della Valle et al. (1994) concluded that bulge-dominated galaxies (NGC 5128, M31, M81, and Virgo ellipticals) have a nova rate per unit H-band luminosity that is more than a factor of 3 lower than that of nearly bulgeless galaxies (LMC and M33). In addition, on the basis of a binary star population synthesis study, Yungelson, Livio, & Tutukov (1997) predict that the nova rate per unit mass of a young population should be much higher than that of an old population. Yungelson et al. find support for that prediction in the nova rates per unit K-band luminosity in the galaxies mentioned above, and they suggest that the apparent dominance of bulge novae in our Galaxy may be due to observational selection effects that favor the discovery of bulge novae over disk novae.

Recently we (Hatano et al. 1997b) have used a Monte Carlo technique together with a simple model for the distribution of dust in the Galaxy to investigate the observability and spatial distribution of Galactic classical novae. We concluded that most Galactic novae are indeed produced by the disk, rather than by the bulge. More specifically, we found the distribution of nova apparent magnitudes and positions on the sky to be consistent with the proposition that the Galactic bulge-to-disk nova ratio is equal to that of the overall Galactic bulge-to-disk mass ratio, which is only about 1/7 (van den Kruit 1990). In this Letter we report results of a study which set out to address the question of whether, similarly, the M31 bulge-to-disk nova ratio is consistent with the M31 bulge-to-disk mass ratio.

2. OBSERVATIONS
Since about 1917, more than 300 novae have been discovered in M31. We concentrate on 191 novae that were discovered (or reported) in major surveys carried out at Mount Wilson (Hubble 1929; Arp 1956) and at Asiago (Rosino 1964, 1973; Rosino et al. 1989) and for which estimates of the peak apparent magnitude, B, are available.

Figure 1 shows the positions on the sky of these novae, on the coordinate system of Capaccioli et al. (1989). At the adopted distance to M31 of 725 kpc (μ = 24.3), 6' corresponds to about 1 kpc. We take M31 to be inclined by 77° and the bulge to be an oblate ellipsoid with an axial ratio of 0.63 (Hodge 1992). The small oval in Figure 1 has a semimajor axis of 18' (about 3 kpc) and defines the “apparent bulge”; apparent bulge novae are those for which the sky positions are within the apparent bulge, and apparent disk novae are those for which positions are not. As discussed below, some of the apparent bulge novae actually are disk novae. The larger ellipse in Figure 1 corresponds to a circle in the disk, of radius
FIG. 1.—Sky positions of 191 novae observed in M31, for which estimates of peak $B$ are available. The M31 major and minor axes are along the $X$ and $Y$ axes, respectively. The large ellipse represents a circle in the inclined disk, of radius 8.8 kpc. Open and filled circles denote novae having $B < 17$ mag and $B > 17$ mag, respectively. The top panel of Figure 2 shows the $B$ distributions for the 167 apparent bulge novae, the 24 apparent disk novae, and the sum of the two. (For comparison, the shape of our model $B$ distribution, to be discussed below, is also shown in Fig. 2, top.)

3. THE MODEL

The Monte Carlo technique that we have developed was inspired by one that was used by Dawson & Johnson (1994) in their study of the observability of historical supernovae in our Galaxy. We (Hatano, Fisher, & Branch 1997a) constructed an independent Monte Carlo code and used it to extend the work of Dawson and Johnson by considering the observability of hypothetical “ultradim” supernovae in the Galaxy and to consider the observability of supernovae, in the model, from an external point of view. Then Hatano et al. (1997b) extended the technique to consider the observability of Galactic classical novae. Here we give a brief description of the model as it is used for this study of novae in M31.

In our previous papers, the Galactic dust was assumed to follow a double exponential law, with a radial scale length of 5 kpc and a vertical scale height of 0.1 kpc. In such a model, the density of the dust peaks right at the center of the Galaxy. In M31, however, the density of the dust is known to peak well out in the disk, not far from where most of the current star formation rate is taking place (Hodge 1992). Following Figure 3 of Xu & Helou (1996), we adopt a simple distribution for the radial dependence of the extinction in M31:

$$A_B = 2.0 - 0.182(8.8 - r) \text{ for } r < 8.8 \text{ kpc} \quad (1)$$

$$A_B = 2.0 - 0.194(r - 8.8) \text{ for } r > 8.8 \text{ kpc} \quad (2)$$

where $A_B$ is the total line-of-sight extinction through the inclined disk of M31. This distribution is generally consistent with the various evidence for the radial dependence of extinction discussed by Hodge (1992). The vertical scale height of the dust is again taken to be 0.1 kpc. In this model, the extinction at $r = 8, z = 0$ kpc is 1.85 mag kpc$^{-1}$, similar to its value at $r = 8, z = 0$ kpc in our Galactic model, 1.9 mag kpc$^{-1}$. The major difference between our adopted distributions of dust in the Galaxy and in M31 is the low dust content in the central regions of M31.

We assume that disk novae in M31 obey a double exponential distribution, with radial and vertical scale lengths of 5 and 0.35 kpc, and the disk is truncated at $r = 20$ kpc. Bulge novae are taken to be distributed as $(R^2 + a^2)^{-1}$, where $R$ is a radial coordinate, $R^2 = r^2 + z^2$, and $a = 0.7$ kpc. Our conclusions do not depend on the particular form of this distribution. The bulge is truncated at $r = 6.4$ kpc, which gives an effective bulge radius of 2.1 kpc (Hodge 1992). For Galactic novae, we used a bulge-to-disk nova ratio of 1/7, based on the estimated bulge-to-disk mass ratio of the Galaxy (van der Kruit 1990). For M31, a more reasonable estimate of the bulge-to-disk mass ratio would be 1/2 (Hodge 1992; Kent 1989), so we adopt this as our default value of the M31 bulge-to-disk nova ratio.

The M31 nova luminosity functions are the same as we used for novae in our Galaxy. They are Gaussian, with dispersions $\sigma(M_B) = 1$, and the mean absolute magnitudes of disk and bulge novae are $-8$ and $-7$, respectively.

4. COMPARISON WITH OBSERVATIONS

Figure 2 (middle) shows our model $B$ distributions for true bulge novae, true disk novae (we do know which model novae...
are from the disk and which are from the bulge), and the sum of the two. As can be seen in Figure 2 (top), the total model B distribution agrees well with the observed B distribution on its bright side, to \( B \approx 16.5 \). The model distribution contains a larger proportion of faint novae than the observed distribution. This is due at least in part to observational selection against faint novae (many faint observed novae had to be excluded from our sample because no estimate of peak \( B \) was available), but it may also be that our adopted luminosity functions contain too many intrinsically dim novae; in any case, this will not affect our main conclusion because it will be based only on the brighter novae. We note that in the mean, the true disk novae are brighter than the true bulge novae. Figure 2 (bottom) is like the middle one, except that now the model novae are divided into apparent disk and apparent bulge novae. Because of the presence of true disk novae masquerading as apparent bulge novae, the difference between the \( B \) distributions of the apparent disk and apparent bulge novae is smaller than the difference between the \( B \) distributions for the true disk and true bulge novae. In Figure 2 (middle) almost all of the bright novae are true disk novae, but in the lower panel, many of those true disk novae become apparent bulge novae. In addition, even though our input model bulge-to-disk nova ratio is only 1/2, the number of apparent bulge novae rivals the number of apparent disk novae. Therefore, according to our model, a substantial fraction of the apparent bulge novae in M31 actually are disk novae.

Some insight into what is going on (at least in the model) can be gained from Figure 3, which shows a side view of the spatial distribution of model novae having \( B < 20 \) mag; for clarity, the vertical scale is expanded by a factor of 5. First, many true disk novae having \( r < 10 \) kpc are seen as apparent bulge novae. Second, while true bulge novae on the top side of the bulge are practically unextinguished, from our vantage point, true bulge novae on the bottom side are significantly extinguished by dust that is well out in the disk, where the extinction is largest. This means that true bulge novae projected onto the top of the bulge are, in the mean, brighter than those projected onto the bottom. As can be inferred from Figure 3, the \( B \) distributions of true disk novae (top and bottom) show a much milder difference.

Figure 3 suggests that the actual M31 bulge-to-disk nova ratio can be estimated by looking at the bottom-to-top ratio (the BTR) of apparent bulge novae — and thus avoiding the issue of the extent to which the bulge has been searched more thoroughly than the disk. Because Figure 2 shows that our model \( B \) distribution only fits the observed \( B \) distribution on its bright side, we now confine our attention to novae having \( B < 17 \) mag. The BTR of observed apparent bulge novae having \( B < 17 \) mag (see Fig. 1) is 0.83 \( \pm 0.15 \), where the uncertainty is from \( N^{1/2} \) statistics. The bottom panel of Figure 4 shows the model distribution of the sky positions of novae having \( B < 17 \) mag. As expected, true disk novae show a mild asymmetry with respect to the major axis, while true bulge novae are strongly concentrated to the top. The top panel of Figure 4 is for an adopted bulge-to-disk ratio of nine, instead of 1/2, i.e., for the case in which M31 novae are overwhelmingly from the bulge. For the model bulge-to-disk ratio of 1/2 (Fig. 4, bottom), the BTR of apparent bulge novae is 0.63. For the bulge-dominated case (Fig. 4, top) the BTR ratio of apparent bulge novae is only 0.33, and the disagreement with the sky
positions of observed novae having $B < 17$ mag (Fig. 1) is obvious.

5. DISCUSSION

The assumption that M31 novae come overwhelmingly from the bulge, together with our simple model, produces results that are inconsistent with observation. Instead, adopting an M31 disk-to-bulge nova ratio that is like the M31 disk-to-bulge mass ratio produces results that are acceptable. This would be consistent with the proposition that the nova rate per unit $K$-band luminosity is approximately constant (Ciardullo et al. 1990; Shafter et al. 1996).

If we take our model literally we can derive the bulge-to-disk nova ratio that actually reproduces the observed BTR of 0.83 ± 0.15. Figure 5 shows the dependence of the model BTR on the percentage of true bulge novae for three different degrees of dustiness—our standard case, as described by equations (1) and (2); twice as dusty; and half as dusty. Our standard model does not require any bulge novae to reproduce the observed BTR of 0.83; within the statistical uncertainty of the observed BTR, the upper limit on the percentage of bulge novae is about 25%, i.e., a bulge-to-disk nova ratio of 0.33. This would be consistent with the proposition that young populations are better at producing novae than old populations (Della Valle et al. 1994; Yungelson et al. 1997). However, Figure 5 shows that if M31 is only half as dusty as we have assumed (see Han 1996), then our upper limit on the percentage of bulge novae would be about 60%, i.e., a bulge-to-disk nova ratio of 1.50. In view of the statistical uncertainties associated with the observed BTR and with our simple model, it probably would be premature to draw any conclusion other than that the M31 bulge-to-disk nova ratio is at least as low as the M31 bulge-to-disk mass ratio.

Now, in order to advance our knowledge of the spatial distribution of novae in M31, what is needed is a carefully controlled search for novae that includes parts of the disk that are unambiguously outside the bulge. It is interesting that of eight M31 novae that were discovered in a recent search by Sharov & Alksnis (1996), only three qualify as apparent bulge novae. As we completed this study we learned that another major search for novae in the disk of M31 is planned (A. Shafter 1997, private communication).

We are grateful to Eddie Baron, Darrin Casebeer, Dean Richardson, and Lev Yungelson for discussions, and to Allen Shafter for correspondence. This work has been supported by NSF grants AST 9417102 and 9417242.

REFERENCES

Arp, H. C. 1956, AJ, 61, 15
Capaccioli, M., Della Valle, M., D’Onofrio, M., & Rosino, L. 1989, AJ, 97, 1622
Ciardullo, R., Ford, H. C., Neill, J. D., Jacoby, G. H., & Shafter, A. W. 1987, ApJ, 318, 520
Ciardullo, R., Ford, H. C., Williams, R. E., Tablyn, P., & Jacoby, G. H. 1990, AJ, 99, 1079
Dawson, P. C., & Johnson, R. G. 1994, JRASC, 88, 369
Della Valle, M., & Duerbeek, H. W. 1993, A&A, 271, 175
Della Valle, M., & Livio, M. 1994, A&A, 286, 786
Della Valle, M., Rosino, L., Bianchini, A., & Livio, M. 1994, A&A, 287, 403
Han, C. 1996, ApJ, 472, 108
Hatano, K., Branch, D., Fisher, A., & Starrfield, S. 1997b, MNRAS, in press
Hatano, K., Fisher, A., & Branch, D. 1997a, MNRAS, in press
Hodge, P. 1992, The Andromeda Galaxy (Dordrecht: Kluwer)
Hubble, E. 1929, ApJ, 69, 103
Kent, S. M. 1989, AJ, 97, 1614
Rosino, L. 1964, Ann. Astrophys., 27, 498
———. 1973, A&AS, 9, 347
Rosino, L., Capaccioli, M., D’Onofrio, M., & Della Valle, M. 1989, AJ, 97, 83
Shafter, A., Ciardullo, R., & Pritchett, C. J. 1996, in Cataclysmic Variables and Related Objects, ed. A. Evans & J. H. Wood (Dordrecht: Kluwer), 291
Sharov, A. S., & Alksnis, A. 1996, Astron. Lett., 5, 680
van der Kruit, P. 1990, in The Milky Way as a Galaxy, ed. R. Buser & R. King (Mill Valley: University Science Books), 331
Xu, C., & Helou, G. 1996, ApJ, 456, 163
Yungelson, L., Livio, M., & Tutukov, A. 1997, ApJ, 481, 127

Note added in proof.—We are indebted to George Jacoby for asking a question that led us to recognize that equations (1) and (2) apply not to the $B$ band but to the $V$ band. This means that we used only three-fourths of the extinction implied by the results of Xu & Helou (1996). Using the full amount only would have strengthened our conclusion that the bulge-to-disk nova ratio is low.