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# DISCOVERY OF CEPHEIDS IN M101

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## ABSTRACT

We report the first definite detection of Cepheid variables in M101, a galaxy of fundamental importance to the extragalactic distance scale. The Cepheids are the most distant ever found, and their discovery illustrates the ready feasibility of sampling through modern digital means these most primary of standard candles over a wide volume of the universe.

*Subject headings:* galaxies: distances — stars: Cepheids

## I. INTRODUCTION

As the nearest Sc I galaxy, M101 has played a prominent role in efforts to measure the cosmological expansion rate. The M101 modulus has been especially critical for calibrating a variety of secondary indicators, perhaps chief among which is the relation between absolute magnitude and luminosity class (see Mould, Aaronson, and Huchra 1980). With the development of new and more accurate methods for securing extragalactic distances, many of the older techniques have become of historical interest only, and one might have assumed that the significance of M101 would have correspondingly decreased. This has turned out not to be the case.

In particular, Rubin *et al.* (1985) have recommended that measurement of $H_0$ be selected as a key project for the Hubble Space Telescope and have identified two leading secondary indicators for accomplishing this goal: the infrared Tully-Fisher method, and the brightest supergiants. The face-on nature of M101 makes it of little value for the IR/H I technique. However, it is with regard to M supergiants that the M101 modulus attains crucial importance in a modern context.

Over the last decade, continued effort has led to the discovery of brighter and brighter red supergiant candidates in M101 (Sandage and Tammann 1974; Humphreys and Strom 1983; Sandage 1983). Humphreys (1983) argues that these stars are excellent standard candles, having a maximum visual luminosity $M_V^{\max} \approx -8$ mag, independent of the luminosity of the parent galaxy. Sandage (1983), however, argues instead for a steep dependence of $M_V^{\max}$ on parent absolute magnitude, as is found for the blue supergiants. Which of these views is correct hinges on the adopted M101 distance. Unfortunately, estimates of this modulus appear to differ by roughly a full magnitude! De Vaucouleurs (1981) lists $(m - M) = 28.5$ mag, van den Bergh (1980) gives $(m - M) = 28.6$ mag, while Sandage and Tammann (1974) find $(m - M) = 29.3$ mag, which when adjusted to the same Hyades modulus used by de Vaucouleurs becomes 29.56 mag. The lower values would be consistent with $M_V^{\max} \approx -8$ mag, as for red supergiants in less luminous galaxies, while the higher values imply that $M_V^{\max} \approx -8.9$ mag (see Sandage 1983).

Because M supergiants hold out such potential for mapping the far reaches of the Hubble flow, it is clearly essential to resolve the question of their proper luminosity calibration. Motivated by this consideration, we began a search for Cepheid variables in M101 2 yr ago using a charge-coupled device (CCD), with the aim of pinning down the correct M101 modulus. Previous photographic searches for Cepheids have yielded negative results (though Sandage and Tammann 1974 noted a possible candidate), leading in turn to the great uncertainty in the current modulus. In this *Letter* we report the initial fruition of our work—the first definite discovery of Cepheids in M101.

## II. OBSERVATIONS AND REDUCTIONS

The observations reported here have been carried out over the last two spring seasons using the KPNO 4 m telescope and an 800 × 800 TI CCD at prime focus, yielding a pixel size of 0".3 × 0".3 and a total imaging area of 4′ × 4′. We settled upon the Kron-Cousins $R$ band as a search wavelength, anticipating that in the red, the better seeing, chip sensitivity, and smaller internal extinction together would more than compensate for the fact that with a typical Cepheid, the amplitude variation at $R$ is ~ 75% of that at $V$, and only ~ 50% of that at $B$ (e.g., Freedman, Grieve, and Madore 1985). Indeed, in the same exposure time our limiting $R$ frames do in fact reach considerably deeper (by 0.5–1 mag) than those at $V$.

Four fields at different locations in the outer spiral arms were selected for monitoring. Owing to poor weather, only one night of data was obtained during the spring 1984 season; happily, a considerably better record ensued for the spring

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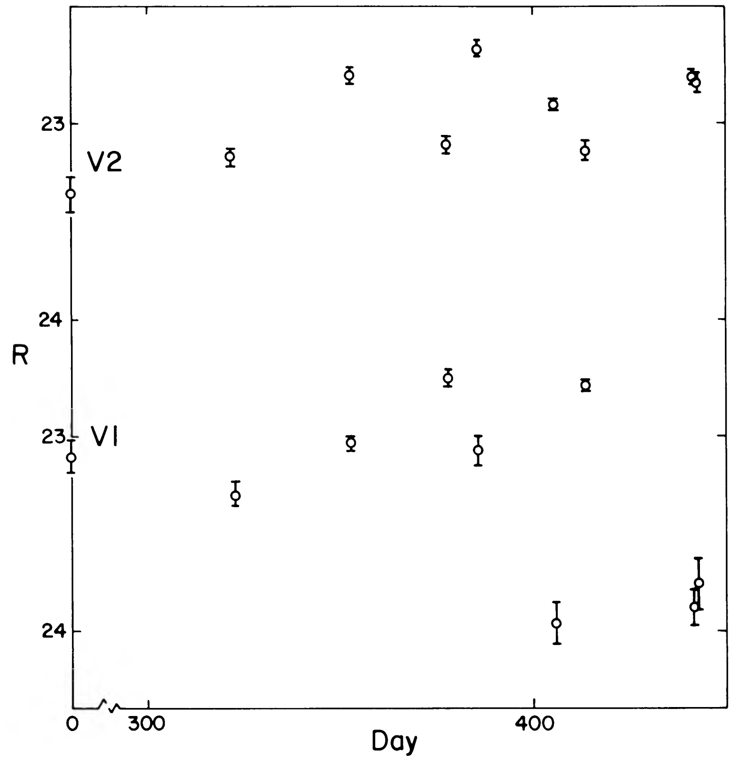


FIG. 1.—Light curves in the $R$ band for two M101 Cepheids. The calendar data is 1984 April 4 (UT) for the first epoch, and 1985 June 21 (UT) for the last epoch. As discussed in the text, the errors for V1 may be somewhat underestimated.

1985 campaign. To date, we have accumulated nine epochs of observation for two of the fields, and six epochs of observation for the other two (all at $R$). In addition, at least one epoch at $V$ was also secured for all four fields. All frames were debiased and flattened in standard fashion while on the mountain.

Total integration times for each field were 2700 s or 3600 s per epoch (depending in part on the seeing), accumulated by averaging separate 900 s exposures. The seeing in the averaged frames, as judged by the half-height width of stellar profiles, ranged from ~ 0″.9 to 1″.6, being typically ~ 1″.2. The observations reach considerably deeper than earlier photographic efforts; generally, *uncrowded* images at $R \approx 24$ mag could be measured with a signal-to-noise ratio of 10.

By eye blinking various combinations of frame pairs in the two main fields, a number of potential variable stars were found. (For this purpose it was unfortunately necessary to both shift and rotate the images to line them up, as the CCD could never be exactly repositioned with the prototype mount in use.) With our as yet limited data base, the exact nature of many of these objects remains ambiguous, though several red long-period variables have been located. Two objects in relatively clear regions exhibiting Cepheid-like variations were identified; subsequent follow-up work confirmed them as Cepheids (see below). The light curves for these two stars are shown in Figure 1.

Photometric calibration of the data was effected using standard stars in M92 (Davis 1985), solving simultaneously for zero point, $V - R$ color term, and extinction. Independent solutions obtained from three clear nights indicated a negligible color term for $R$, and a color term of ~ 3% for $V$; residuals about these solutions were always of order 0.01 mag. Several isolated stars, judged internally constant to 0.01 mag, were chosen in each M101 field to serve as local standards, and all subsequent variable star photometry was referred to these objects, allowing for accurate measurements to be made even under nonphotometric conditions. Again, the independent calibrations provided a consistency check on the adopted magnitudes of the local standards, which we believe are good to better than 0.02 mag.

The final photometry in Figure 1 was determined using DAOPHOT, the profile-fitting code developed by Peter Stetson and now in wide use (Stetson 1985). The errors shown were generated by the PEAK routine; these are based solely on the uncertainty in the profile fit and assume that background sky is perfectly determined. As a check, independent error estimates were calculated from the photon statistics in the star and sky, yielding values in reasonable agreement with those in the figure.

This does not tell the whole story. In particular, the typical background field in M101 is highly variable, owing to the presence of both bright stars and extended emission-line regions, and an underlying disk giant population that is near the limit of resolution. This in turn produces dramatic changes in the character of the background with only small variations in seeing. Under such conditions, and given the modal nature of sky finding routines in use, the question of where to properly set sky becomes of critical concern. We emphasize that with the type of crowding involved here, *photometric measure of faint objects must be exercised with extreme caution.*

To constrain any possible bias introduced by modal rejection effects in the sky setting routine of DAOPHOT, the following tests were made: First, DAOPHOT photometry was performed using two separate sky annuli. Second, all measurements were repeated using the Mountain Photometry Code (an aperture program developed by H. Butcher in use at NOAO) in automatic sky mode, again using two separate sky annuli. Finally, the Mountain Code was once more employed, but sky for each epoch of observation was set individually by eye. For the two stars in Figure 1, the differing approaches all led to results consistent to within $\sim 0.1$ mag (though for some of our more crowded variable candidates the agreement in this regard was much poorer). We conclude from all this that the errors shown in Figure 1 are probably underestimated for V1, but not by much; the errors for the more isolated star V2 are good estimates.

There is no question that the stars in Figure 1 are variables. We searched for possible periods between 10 and 100 days by examining phase diagrams within this range, spaced one-half day apart. Somewhat to our surprise, we found that periods for both stars could be determined to within 2 days, and the resulting phase diagrams and best guess periods are shown in Figure 2. The first epoch obtained in the spring of 1984 was critical for eliminating possible aliases which might otherwise have been present. (As an alternative, we tried the two-epoch period search approach of Madore and Freedman 1985 but could not achieve sensible results.)

The number statistics of bright variable stars in the Magellanic Clouds, M31, and NGC 300 have been summarized recently by Madore and Freedman (1985). Roughly two-thirds of variables found are classical Cepheids, while one-sixth are irregulars, with the remainder made up of long-period variables, eclipsing variables, and W Virginis stars. The $V-R$ colors measured on 1985 March 23 (UT) (the third epoch) were $0.65 \pm 0.10$ for V1 and $0.40 \pm 0.05$ for V2. The colors and luminosities, combined with the characteristic asymmetric phase diagrams in Figure 2 (e.g., Moffett and Barnes 1985), leave little doubt that the two stars are indeed Cepheids.

The one unusual aspect of the photometry is the large amplitude of variation for V1. The largest amplitude variables in the Galaxy and in the Magellanic Clouds (Schaltenbrand and Tammann 1970; Madore 1985) would imply a maximum value of $\sim 1.0$ mag for $\Delta R$, as opposed to $\Delta R \approx 1.2$ mag suggested by Figures 1 and 2. This is probably of little concern, given the photometric errors when the star was faint, and keeping in mind the possible effects of biased sky values discussed above.

A finding chart for the two Cepheids is provided in Figure 3 (Plate L7). Their positions (1950 epoch, $\pm 1''$ accuracy) are $14^h00^m32^s.2$, $+54°32'26''$ (V1) and $14^h00^m29^s.5$, $+54°32'38''$(V2). The stars are about 9′ west and 3′ south of the M101 nucleus.

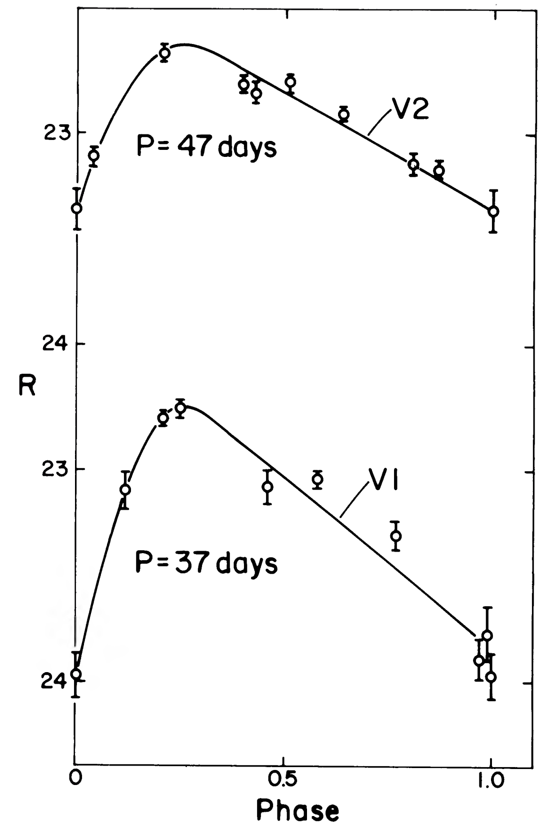


FIG. 2.—Phase diagrams for the two Cepheids in Fig. 1 obtained with the listed periods (rounded to the nearest day). Such phase diagrams look essentially random when plausible periods more than two days from those shown are used. Zero phase has been set at the lowest luminosity observation, which has also been replotted at phase 1.0.

### III. DISCUSSION

Present day estimates of the modulus to M101 are based primarily on the *lack* of Cepheid detections (e.g., Sandage 1983). Hence, even the discovery of just two Cepheids can considerably improve the situation. For this purpose, we shall examine the relative modulus between M101 and the LMC implied by the preliminary light curve parameters derived from Figure 2.

Unfortunately, the available photometry is too limited at present to directly construct a reliable *P-L* relation for the LMC at $R$ (see Madore 1985). We instead start with Caldwell and Coulson's (1985) *P-L* relation at $V$ based on 73 Cepheids, for which $\langle V \rangle_0 = 17.05 - 2.69 \log P$ ($\sigma = 0.23$ mag). These authors also find a period-color relation for 19 Cepheids given by $(V-I)_0 = 0.36 \log P + 0.37$. Using the fact that to a good approximation $(V-I) \approx 2(V-R)$ (Madore 1985), we derive $\langle R \rangle_0 = 16.86 - 2.87 \log P$. Note that the slope in this relation is in good agreement with the value of 2.89 obtained from a least-squares fit (for $\log P < 2$) to the copious amount of SMC $R$ photometry summarized by Madore (1985); we have refrained from employing these latter data, though, because of concerns pertaining to the photometric quality of the measurements and the question of abundance effects.

From Figure 2, we estimate intensity weighted means of $\langle R \rangle \approx 23.2$ mag for V1 and $\langle R \rangle \approx 22.9$ mag for V2, values we believe good to $\pm 0.1$ mag. Both stars then give a relative M101–LMC modulus of 10.8 mag. The distance to M101 itself follows upon adoption of an LMC modulus. However, there is considerable dispute even over the distance to the LMC. Using the *P-L-C* relation and an absolute calibra-

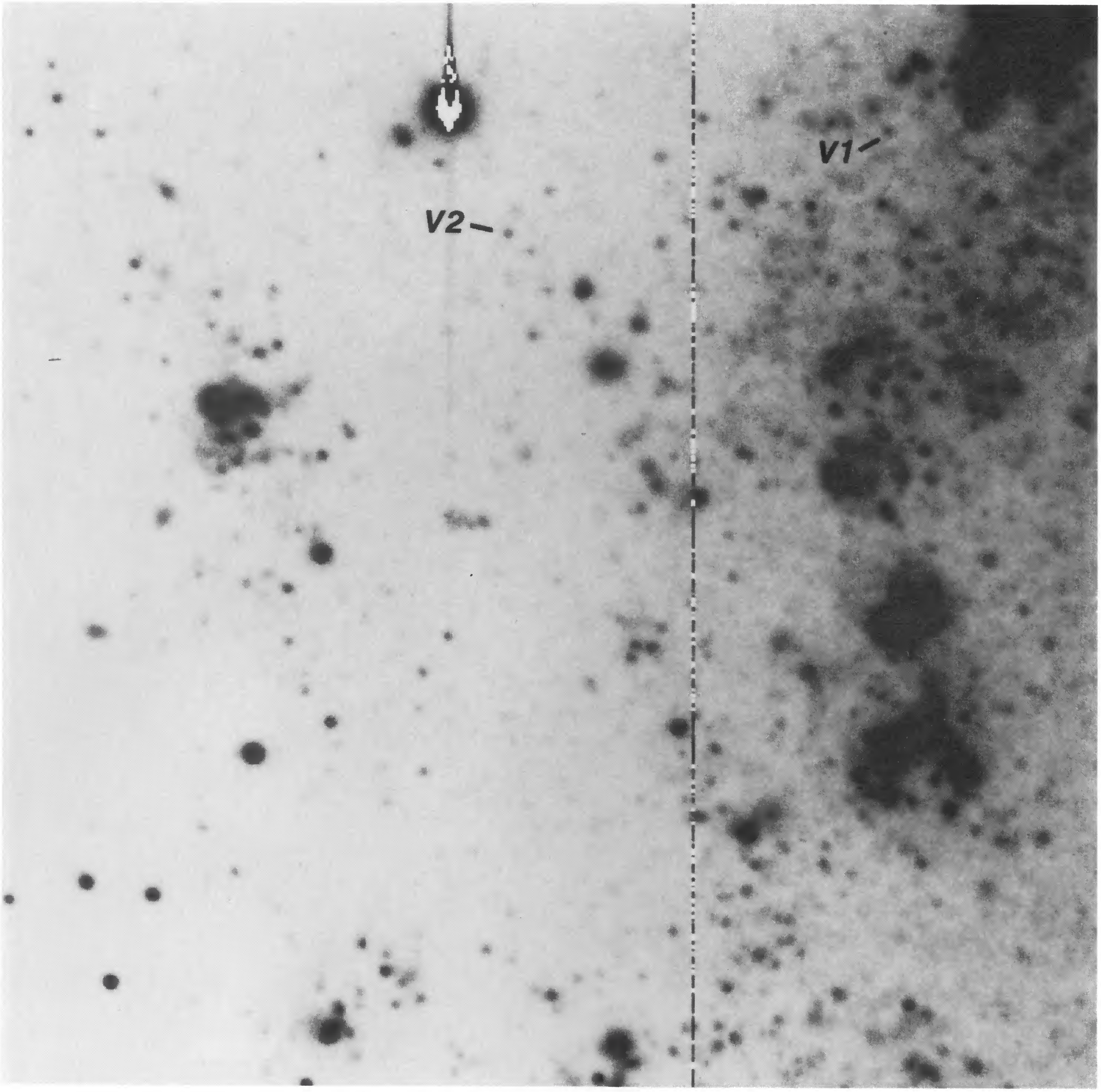


FIG. 3.—An $R$ band finding chart for two Cepheids discovered in M101. South is at the top, east is to the right, and the distance between the two marked stars is 43″. The image was produced from the mean of three 900 s exposures taken with the KPNO 4 m telescope and TI CCD; only a corner 400 × 400 pixel area of the 800 × 800 pixel frame is shown. The observation was made on 23 March 1985 (UT), the third epoch of measure (see text), when both Cepheids were near $R \approx 23$ mag.

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tion based primarily on galactic main sequence fitting, Caldwell and Coulson (1985) find $(m - M)_0 = 18.65$ mag. On the other hand, Schommer, Olszewski, and Aaronson (1984; see also Andersen, Blecha, and Walker 1985) employ direct main-sequence fitting to several Large Cloud clusters to obtain $(m - M)_0 = 18.2$ mag, a value in good agreement with the modulus derived from the *infrared P-L* relation calibrated via Schmidt's (1984) H$\beta$ photometry. Intermediate between these results is the modulus of 18.4 mag found by Walker (1985) from study of RR Lyrae stars.

Making allowance for uncertainty in LMC distance, an M101 modulus in the range 29.0–29.5 mag follows. Any adjustment for internal absorption in M101 would lower the estimate (and such a correction may be necessary for V1 given the location and slightly red color of this star). Abundance effects also remain of concern, though the sensitivity of the *P-L* relation to metallicity is apparently less than that of the *P-L-C* relation (Iben and Tuggle 1975; Gascoigne 1974). Bearing these caveats in mind, it nonetheless appears that our results are more in line with the higher modulus advocated by Sandage (1983), than with the lower one of de Vaucouleurs (1978).

Should further work confirm the higher M101 modulus, several significant implications bearing on the M supergiant problem discussed in § I follow. First, a dependence of $M_V^{max}$ on parent absolute magnitude would definitely be established. This would in turn make practical application of the method more difficult, as *a priori* knowledge of intrinsic galaxian luminosity, obtained for instance via the problematic luminosity class, would then be required. Furthermore, the reason brightest M supergiants had been thought to be good standard candles involved the onset of instability effects in stars more massive than $M \approx 50\ M_\odot$, preventing their evolution to the redward part of the H-R diagram. However, Humphreys *et al.* (1985) have recently obtained IR photometry of candidate red supergiants in M101, and the derived bolometric magnitudes imply progenitor masses much greater than 50 $M_\odot$ for the large M101 modulus suggested here. This seemingly undermines the entire physical basis of the red supergiant method, reducing it simply to a mere statistical effect, as with the blue supergiants. Thus, these various considerations suggest that M supergiants may not be quite as suitable a distance indicator as was once thought.

In closing, we note that this article is very much a report of work in progress. Over upcoming observing seasons we hope to continue the observations so as to substantially increase the present Cepheid sample and accurately tie down the relevant light curve parameters. We also are planning to acquire multicolor *BVRI* data in order to contain possible internal absorption effects. Perhaps the greatest significance of the present results is in demonstrating that the properties of Cepheids can now be studied over a much wider volume of the universe than was heretofore thought. While we believe that settling the current controversy over the value of $H_0$ will ultimately require the use of the Hubble Space Telescope, it is equally clear that a substantial foundation for this marvelous instrument to build upon can now be laid from the ground.

With great pleasure we thank the Kitt Peak Director and staff for relaxing the normal constraints involved in running a national facility and scheduling time for this project in a manner essential for its success. We also acknowledge Ed Olszewski for introducing us (as well as the rest of the Tucson community) to DAOPHOT. Work reported here was partially supported with funds from National Science Foundation grant AST 83-16629.

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