“Space is a pretty dynamic place, and there is a lot going on in this area called Corona Australis Complex,” said Debra Ceravolo. Peter Ceravolo acquired the data from San Pedro de Atacama in Chile, using the Ceravolo 300 Astrograph at f/4.9 on a Paramount ME. Debra processed the image using MaximDL and PixInsight. Total exposure was 7.2 hours: LRGB: 285, 50, 30 and 35 minutes. “Some dust (blue reflection nebula) is getting lit up by nearby bright stars and the dark dust cloud is not. It is all about 500 light-years away except the globular cluster (NGC 6723) is 30,000 light-years away. Put that in perspective!” she says.
President’s Corner

by Christopher Gainor, Ph.D., Victoria Centre (cgainor@shaw.ca)

For most RASC members, getting together usually means some activity within a Centre, such as a monthly meeting, observing night, annual banquet, or even an informal activity like the weekly Astro Café that has become a popular event in my home Centre in Victoria.

Getting the Society together at the National level is more difficult because, as our former Prime Minister, William Lyon Mackenzie King, once observed, in Canada we have too much geography.

For much of its existence, the RASC’s only National event was its Annual General Meeting, which, until 1960, always took place in Toronto. That event traditionally involved only dealing with Society business, but in 1959 the meeting was expanded to include papers on astronomy. The following year the enlarged event took place in Montréal, marking the beginning of our annual General Assemblies.

The GAs that followed over the past six decades have usually taken place on university campuses in various parts of the country, usually on either the Victoria Day or, more recently, the Canada Day long weekends. National Council meetings, Society banquets, the Annual General Meeting and paper presentations have been staples of every GA.

For many years Centres competed to host the GA, but in recent years interest in hosting these meetings has declined to the point where the 2019 GA was largely organized out of the National Office. There are several reasons for this change, but a major one is that General Assemblies based at universities have become more complicated to organize and less convenient for many people to attend.

A few years ago I asked for input from interested members and then wrote a report suggesting that we make some changes to the format of GAs. In 2019, we held the GA in the middle of June instead of on a long weekend, a change that was seen as successful.

Another idea was to move the GA away from universities. The 2020 General Assembly is taking place the weekend of June 5 to 7 at the Executive Plaza and Conference Centre in Coquitlam, B.C., which is conveniently located near a stop on Greater Vancouver’s SkyTrain system. In a nod to our history, one evening’s activities will take place at Simon Fraser University in Burnaby and include a visit to the Trottier observatory on campus.

While hotel accommodations are more expensive than university residences, meetings in hotels are generally easier.

For the 2020 GA, the National Office is bringing together a number of speakers to present talks on topics related to the current state of the astronomical sciences. It contains articles on Canadian astronomers and current activities of the RASC and its Centres, research and review papers by professional and amateur astronomers, and articles of a historical, biographical, or educational nature of general interest to the astronomical community. All contributions are welcome, but the editors reserve the right to edit material prior to publication. Research papers are reviewed prior to publication, and professional astronomers with institutional affiliations are asked to pay publication charges of $100 per page. Such charges are waived for RASC members who do not have access to professional funds as well as for solicited articles. Manuscripts and other submitted material may be in English or French, and should be sent to the Editor-in-Chief.
Cepheid Variables in the Andromeda Galaxy from Simon Fraser University’s Trottier Observatory

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Abstract

This is a report on observations of 17 Cepheid variable stars in the Andromeda Galaxy, from Simon Fraser University’s Trottier Observatory. The observatory is a teaching and public outreach facility with a 0.7-m aperture telescope under suburban skies. The observations were done as a group project by a team that included students, staff, and faculty at the university, and members of the Vancouver Centre of the Royal Astronomical Society of Canada. The Cepheid periods range from about 7 to 44 days, and observations were made on 26 nights over the course of two years. Images were taken through a luminance filter, and the instrumental magnitudes were converted to the Johnson-Cousins V-band using a calibration procedure whose precision is thoroughly characterized. The mean apparent magnitudes range from about 19.3 to 20.7, and they exhibit a correlation with the period that clearly reproduces the famous period-luminosity (PL) relation, which was discovered by Henrietta Leavitt in 1912, and that was the basis of the famous period-luminosity relation discovered by Henrietta Leavitt. We estimated the distance modulus $\mu$ (difference between apparent and absolute magnitudes) using a well-established calibration of the Leavitt relation, along with a correction for interstellar extinction from a professional study of this region of M31. We obtained $\mu = 24.37 \pm 0.21$, which is in excellent agreement with the known value, and corresponds to a distance of $2.44 \pm 0.25$ million light-years.

I) Introduction

The combination of increasingly affordable large-aperture telescopes, and large-format cooled CCD cameras, has revolutionized the capabilities of amateur astronomers. The abundance of amateur astronomical images of astonishing depth and quality is the most prominent sign of this technology shift. Amateurs also conduct original research with their own equipment, including supernovae searches, variable star measurements, comet hunting, asteroid photometry, and other investigations. However, a major impediment to the pursuit of original research is the long-term commitment in time and effort that is generally required, with no assurance that a lengthy investigation will produce a significant new finding.

For those who want to experience the excitement of doing real science, there is a much more accessible alternative to attempting original research, which is to reproduce important discoveries. “Rediscovery” projects can be as sophisticated and satisfying as original research, but they can be tailored to make successful completion much more likely, and to be achievable within a predictable time frame. Reproducing classic experiments is a routine part of university education in many branches of science, and university teaching observatories have long been used to this end.

A recent book by Robert Buchheim [1] details a remarkably comprehensive array of astronomical “rediscovery” projects, of varying degrees of sophistication. These projects can be done using modest equipment, and are well suited to amateur astronomers, and to implementation at university teaching observatories. The penultimate project in Buchheim’s book is to measure the light curve of the first Cepheid variable star to be discovered in the Andromeda Galaxy, which Edwin Hubble recorded in 1923 on a now-legendary photographic plate (see e.g. Ref. [2]). The goal of Buchheim’s project is to estimate the distance to M31. This is to be done by comparing the average apparent magnitude of Hubble’s first Cepheid (hereafter referred to as “H1”) with its absolute magnitude, as given by the famous period-luminosity (PL) relation, which was discovered by Henrietta Leavitt in 1912, and that was the basis of Hubble’s historic estimate of the distance to Andromeda.

Prior to the publication of Buchheim’s book, a sophisticated measurement of the ephemeris of H1 was done by a largely non-professional group that included Buchheim, working under the auspices of the American Association of Variable Star Observers (AAVSO) [3]. That study was undertaken at the request of the Hubble Heritage Project, which highlighted the work in an on-line press release [4]. A group from the AAVSO also published a follow-up study [5].

Buchheim’s book, along with the Hubble Heritage and AAVSO publications, inspired the study that is the subject of this report. We undertook a much more ambitious project than the one suggested by Buchheim, by observing a large number of Cepheids in Andromeda, and our work differs in purpose and scope from the AAVSO studies. This work was done as a group project at the Simon Fraser University (SFU) Trottier Teaching and Outreach Observatory, by a team that included
SFU students, staff and faculty, and members of the Vancouver Centre of The Royal Astronomical Society of Canada. The project was conceived of and directed by the lead author, who also did the data analysis.

We monitored 17 Cepheids, including H1, with periods ranging from about 7 to 44 days. Our data set, accumulated over the course of two years, is large enough to independently observe Leavitt’s PL relation (also known as Leavitt’s Law), a dramatic “rediscovery” with a significance that would be hard to surpass! A data set that covers a wide range of periods is also required for a reliable determination of the distance, since the PL relation does not apply to individual Cepheids, but instead characterizes ensemble averages of these stars (see e.g. Ref. [6]).

The SFU observatory opened in April of 2015 and is the anchor of a high-profile public space devoted to science, situated near the centre of the Burnaby campus (see Figure 1). The facility is used for public outreach, student education, and as a resource for local amateur astronomers, especially members of the RASC Vancouver Centre. The observatory houses a PlaneWave Instruments CDK700 alt-az telescope system, with a 0.7-m aperture operating at f/6.5, under a 6-m Ash dome. Observatory equipment includes a Finger Lakes Instruments 16-Megapixel imaging camera, and a high-resolution echelle spectrograph made by Shelyak Instruments. Some images taken at the observatory have been published [7][8], along with a report on a “rediscovery” of exoplanet τ Boötis b from radial-velocity measurements [9]. Other images and studies have been produced by observatory users, including students from local high schools; some of this work is documented on the observatory website [10].

The rest of this paper is organized as follows. In Section II, we give a brief overview of Cepheid variables, emphasizing properties that are relevant to our study. In Section III, we identify the Cepheids we studied, and the reference and comparison stars used for photometric calibration, and we summarize some parameters of the observing campaign. In Section IV, we detail the photometric reduction of the raw instrumental magnitudes, which were obtained with a luminance filter in order to maximize the signal-to-noise, and must be converted to a standard bandpass, here taken to be the Johnson-Cousins V-magnitude. In Section V, we analyze the reduced data: we estimate the periods, plot light curves, compute mean magnitudes, analyze the correlation between apparent magnitude and period (thereby reproducing Leavitt’s Law), and finally we estimate the distance to Andromeda, after correcting for extinction due to interstellar dust. In Section VI, we briefly summarize our results, and provide suggestions for further work.

We hope that these results will encourage amateur astronomers and other university teaching observatories to attempt similar projects. To that end, we have formulated this report as a comprehensive guide to the data collection and analysis techniques. We have also included enough theoretical background to put the work in context, and we have provided a fairly comprehensive set of references.

II) Cepheid variables: a brief overview

Cepheid variables form a critical “rung” in the so-called cosmic distance ladder, the sequence of techniques used by astronomers to determine the distances to objects that are at progressively greater remove (for a thorough and accessible introduction to these techniques, see Ref. [11]). These methods generally use one form or another of astronomical “standard candle.” These are classes of astrophysical objects all having the same luminosity, or luminosities that are strongly correlated with more readily measured attributes, and that are luminous enough to be seen at the distance scale of interest.

Cepheid variables qualify as standard candles because their mean luminosities are strongly correlated with the period of pulsation, and they play a fundamental role in modern astronomical research. Cepheids are used to determine distances to relatively nearby galaxies, in order to calibrate the luminosity of Type Ia supernovae, which in turn are used for cosmological distance estimates (see e.g. Ref. [12]). A very notable study of Cepheid variables was one of the three principal initial objectives of the Hubble Space Telescope (known as “Key Projects”), which measured the Hubble constant H0 [13][14].

Cepheids have a number of favourable attributes, in addition to the period-luminosity relation, which include [13]: large luminosities (as much as 100,000 times the luminosity of the Sun); light curves with large amplitudes and a distinctive saw-tooth shape, illustrated in Figure 2, which aid in their...
identification; and their relative abundance in spiral galaxies, which means that many independent objects in a given galaxy can be studied simultaneously. The use of the Cepheid yardstick also has challenges, which include [13]: significant extinction and reddening caused by dust along the line of sight through the Milky Way, and in the host galaxy (Cepheids are post-main-sequence stars associated with dusty star-forming regions); the dependence of the period-luminosity relation on the composition (metallicity) of Cepheids in different galaxies, and within different regions of the same galaxy; and uncertainties in the period-luminosity relation [12].

In its simplest form, the period-luminosity relationship, also known as Leavitt’s Law, is given by

\[
\langle M_X \rangle = -a_X \log_{10} P_d - b_X
\]

(1)

where \( \langle M_X \rangle \) denotes a mean absolute magnitude in wavelength band \( X \) (i.e. \( X = B, V, R \) etc.), \( P_d \) is the period of pulsation in days, and \( a_X \) and \( b_X \) are constants that take on different values in different bands. The PL relationship in several wavelength bands is illustrated in Figure 3 [14]. The scatter in the data is not due to measurement uncertainties, but instead reflects a statistical property of Eq. (1), which applies to ensembles of Cepheids, not to individual stars, which can differ in luminosity for a given period due to intrinsic differences such as metallicity.

The Hubble Space Telescope Key Project to measure \( H_0 \) adopted the following PL relation for the visual band [13], based on studies of Cepheids in the Large Magellanic Cloud

\[
\langle M_V \rangle = -2.76(3) \log_{10} P_d - 1.46(4)
\]

(2)

where the numbers in parentheses are uncertainties in the last digit of the constants. The spread in the absolute magnitudes about the mean relation given by Eq. (2) has a standard deviation of approximately ±0.16 magnitudes [13].

The mechanism that generates pulsations of Cepheid variables is well understood and is similar to a heat engine (see e.g. Refs. [11], [14]). During the contraction phase, energy is trapped in the star’s interior and the pressure increases, until the contraction is reversed; the energy is then released as work is done to
expand the star’s outer layers against gravity, while the pressure decreases until the expansion halts and the next contraction phase begins. Cepheid pulsations are driven by a region in the star of partially ionized helium, which traps energy during a contraction by producing further ionization of the gas. In an ordinary star, by contrast, the energy generated by a contraction causes the temperature of the gas to increase, which also increases the temperature gradient (i.e. the opacity is reduced), which allows the energy to escape, and damps the pulsation. Simple physical arguments can also be used to derive the form of the period-luminosity relation, including a reasonable estimate of the coefficient of the logarithm in Eq. (4).

III) M31 Cepheids: Observations

We did a literature search to identify Cepheids that could be observed with our facility. This led us to publications by Baade and Swope (B&S) from the mid-1960s, on hundreds of variable stars, in three regions of M31, which were observed with the Palomar 200-inch telescope [15] [16]. These papers include photographic plates with the locations of the variables, which we compared with our own images to identify possible targets. We note that a modern study of the B&S fields was published by Freedman and Madore [17]; this paper contains a great deal of valuable information, including estimates of the extinction along the line of sight to each field.

B&S Field I [16] has Hubble’s first Cepheid, and we identified 16 additional variables in that field that are bright enough to be detected from our suburban location, and that lie within a single field of view of our imaging system (about 27′ square).

Of the Cepheids in our study, four were identified by Hubble, which we label with an “H” prefix, and the rest by B&S, which we identify with a “V” prefix and their numbering scheme. We list some properties of our targets in Table 1, including our final results for the periods and mean magnitudes. The mean luminosities of these stars range from about 3000 to 20,000 solar luminosities.

A finder image that identifies the Cepheids is shown in Figure 4, along with eight photometric standard stars that we use, whose properties were taken from databases compiled by the American Association of Variable Star Observers (AAVSO) [18] [19]. AAVSO identifiers and data for these stars are listed in Table 2, along with identifiers that we use in Figure 4 and Table 1 — Cepheid variables observed in this study. The periods are taken from B&S [16], except for the two cases identified with a superscript, where our estimates differ appreciably (B&S period for a: 11.58 days; and for b: 28.16). \( \phi_{\text{shift}} \) are phase shifts introduced in Eq. (7). \( \langle m_V \rangle \) tabulates our final estimates of the mean visual magnitudes.

<table>
<thead>
<tr>
<th>Cepheid</th>
<th>Period (days)</th>
<th>( \phi_{\text{shift}} )</th>
<th>( \langle m_V \rangle )</th>
</tr>
</thead>
<tbody>
<tr>
<td>V146</td>
<td>7.39</td>
<td>0.36</td>
<td>20.62(20)</td>
</tr>
<tr>
<td>V117</td>
<td>7.89</td>
<td>0.04</td>
<td>20.66(17)</td>
</tr>
<tr>
<td>V125</td>
<td>11.80</td>
<td>0.89</td>
<td>20.06(17)</td>
</tr>
<tr>
<td>V54</td>
<td>12.15(^a)</td>
<td>0.73</td>
<td>20.46(15)</td>
</tr>
<tr>
<td>V92</td>
<td>14.35</td>
<td>0.21</td>
<td>20.29(13)</td>
</tr>
<tr>
<td>V56</td>
<td>14.40</td>
<td>0.61</td>
<td>20.04(10)</td>
</tr>
<tr>
<td>V57</td>
<td>14.62</td>
<td>0.78</td>
<td>20.08(14)</td>
</tr>
<tr>
<td>V100</td>
<td>16.71</td>
<td>0.63</td>
<td>20.15(25)</td>
</tr>
<tr>
<td>H18</td>
<td>18.52</td>
<td>0.74</td>
<td>20.04(11)</td>
</tr>
<tr>
<td>H17</td>
<td>18.77</td>
<td>0.74</td>
<td>19.82(11)</td>
</tr>
<tr>
<td>V130</td>
<td>20.19</td>
<td>0.59</td>
<td>20.18(14)</td>
</tr>
<tr>
<td>H3</td>
<td>27.03</td>
<td>0.58</td>
<td>19.38(7)</td>
</tr>
<tr>
<td>V128</td>
<td>27.24</td>
<td>0.20</td>
<td>20.39(16)</td>
</tr>
<tr>
<td>V66</td>
<td>29.01(^b)</td>
<td>0.82</td>
<td>19.88(12)</td>
</tr>
<tr>
<td>H1</td>
<td>31.38</td>
<td>0.97</td>
<td>19.26(5)</td>
</tr>
<tr>
<td>H16</td>
<td>41.12</td>
<td>0.19</td>
<td>19.55(7)</td>
</tr>
<tr>
<td>V120</td>
<td>44.88</td>
<td>0.97</td>
<td>19.52(10)</td>
</tr>
</tbody>
</table>

Table 1 — Cepheid variables observed in this study. The periods are taken from B&S [16], except for the two cases identified with a superscript, where our estimates differ appreciably (B&S period for a: 11.58 days; and for b: 28.16). \( \phi_{\text{shift}} \) are phase shifts introduced in Eq. (7). \( \langle m_V \rangle \) tabulates our final estimates of the mean visual magnitudes.

Figure 4 — Greyscale-inverted finder image for the 17 Cepheid variable stars that were monitored in this study (denoted by H# or V#), along with the 3 reference stars that were used for photometric calibration (R#), and 5 check stars that were used to monitor the quality of the photometry (C#). This image was taken on 2017 December 8 (UT). The J2000 coordinates of the centre of the field are RA 00h 42m 4s, and Dec +41° 06′ 55″. The field is “visually” oriented, with a position angle of 13° from North, an angular size of about 27.8′ square, and a plate scale of about 0.81″/pixel. Contrast enhancement and sharpening were used here to aid in the identification of the targets (only dark subtractions and flat-field corrections were applied to images that were used for photometric analysis).
later in the paper; we used three of these stars as calibration references (“R” prefix), and the others as check stars (“C” prefix).

This project traces back to an observatory imaging program that serendipitously imaged H1 on a night in the fall of 2015. Several months passed before we realized that H1 had been captured, so we had to wait until the fall of 2016 to continue taking data, and by that time we had conceptualized the full project. We took measurements again in the fall of 2017 and ended up with 26 nights in all; some of the observations are grouped in bunches of a few closely spaced nights, typically spanning about a week, owing to the short periods of good weather that are typical of the west coast in the fall season. Some information about the observation campaign is given in Table 3, including dates and exposure times, along with the averaged full-width at half-maximum (FWHM) of the imaged stars, as a measure of image quality.

Integration times ranged from as little as 20 minutes, to more than 90 minutes. A luminance filter was used in order to maximize the signal-to-noise. Single-frame exposure times of 2 minutes were typical, limited in part by sky glow. Seeing conditions varied widely, with star profiles typically less than about 2.5″, and one extremely turbulent night at 3.6″ that still yielded useful data. Sky transparency also varied widely, and a bright Moon was in the sky on some nights. Several variables were not imaged on the first five nights, as we had yet to determine the optimal coordinates for the field of view, and some of the fainter variables could not be detected on nights with poorer seeing and/or transparency. Targets that were not observed on a given night are listed in Table 3. Despite the widely variable observing conditions, differential photometric calibration produces consistent results for the magnitudes of check stars spread across nearly the entire field of view, over the entire observing campaign, as we demonstrate in the next section.

### IV) Photometric reduction

Dark frames and twilight flats were applied to individual frames, which were then stacked to produce an integrated image. No other processing was applied to images used for photometry. To estimate stellar magnitudes, we used standard differential photometry, in which the brightness of a target

<table>
<thead>
<tr>
<th>AAVSO ID</th>
<th>Our ID</th>
<th>( m_v )</th>
<th>( m_B - m_v )</th>
</tr>
</thead>
<tbody>
<tr>
<td>000-BJV-791</td>
<td>R143</td>
<td>14.272(38)</td>
<td>0.680(64)</td>
</tr>
<tr>
<td>000-BJV-794</td>
<td>R157</td>
<td>15.679(32)</td>
<td>0.624(64)</td>
</tr>
<tr>
<td>000-BJV-795</td>
<td>R159</td>
<td>15.858(29)</td>
<td>0.686(53)</td>
</tr>
<tr>
<td>000-BBB-973</td>
<td>C139</td>
<td>13.813(49)</td>
<td>0.546(80)</td>
</tr>
<tr>
<td>000-BBB-974</td>
<td>C140</td>
<td>14.000(18)</td>
<td>0.587(30)</td>
</tr>
<tr>
<td>000-BJV-792</td>
<td>C147</td>
<td>14.704(9)</td>
<td>0.772(22)</td>
</tr>
<tr>
<td>000-BJV-798</td>
<td>C163</td>
<td>16.285(49)</td>
<td>0.914(96)</td>
</tr>
<tr>
<td>000-BJV-800</td>
<td>C167</td>
<td>16.672(44)</td>
<td>0.805(74)</td>
</tr>
</tbody>
</table>

Table 2: Photometric standard star data taken from the AAVSO Variable Star Plotter [18], except for C139, which is from the AAVSO APASS database [19].

<table>
<thead>
<tr>
<th>Date (UT)</th>
<th>Exp. / FWHM</th>
<th>Not observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015-11-16, 06:30</td>
<td>48m / 2.2&quot;</td>
<td>V100, H16</td>
</tr>
<tr>
<td>2016-09-05, 06:30</td>
<td>42 / 2.2</td>
<td>V146, V117, H17, V128, H16, V120</td>
</tr>
<tr>
<td>-09-22, 06:45</td>
<td>36 / 2.0</td>
<td>V146, V117, H17, V128, H16, V120</td>
</tr>
<tr>
<td>-09-26, 05:45</td>
<td>98 / 1.8</td>
<td>V146, V117, H17, V128, H16, V120</td>
</tr>
<tr>
<td>-09-28, 04:50</td>
<td>54 / 2.9</td>
<td>V117, V56, H17, V128, H16, V120</td>
</tr>
<tr>
<td>-09-29, 07:10</td>
<td>82 / 2.1</td>
<td></td>
</tr>
<tr>
<td>-10-10, 03:45</td>
<td>76 / 2.1</td>
<td>V100</td>
</tr>
<tr>
<td>-10-11, 03:30</td>
<td>60 / 3.1</td>
<td>V117, V54, V100, V128</td>
</tr>
<tr>
<td>-10-29, 05:45</td>
<td>20 / 2.3</td>
<td></td>
</tr>
<tr>
<td>-12-01, 08:00</td>
<td>26 / 2.5</td>
<td></td>
</tr>
<tr>
<td>-12-05, 02:30</td>
<td>86 / 2.3</td>
<td></td>
</tr>
<tr>
<td>2017-01-12, 03:30</td>
<td>76 / 2.8</td>
<td>V100</td>
</tr>
<tr>
<td>-01-13, 03:30</td>
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<td>V146, V100, H18, V54</td>
</tr>
<tr>
<td>-01-24, 03:30</td>
<td>72 / 2.0</td>
<td></td>
</tr>
<tr>
<td>-02-01, 03:30</td>
<td>90 / 3.6</td>
<td>V146, V117, V100</td>
</tr>
<tr>
<td>-09-15, 07:30</td>
<td>86 / 2.2</td>
<td></td>
</tr>
<tr>
<td>-09-24, 05:00</td>
<td>88 / 2.3</td>
<td>V100</td>
</tr>
<tr>
<td>-09-27, 05:00</td>
<td>86 / 2.0</td>
<td></td>
</tr>
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<td>-09-29, 04:45</td>
<td>90 / 1.9</td>
<td>V146</td>
</tr>
<tr>
<td>-12-06, 03:15</td>
<td>86 / 2.5</td>
<td></td>
</tr>
<tr>
<td>-12-07, 03:45</td>
<td>77 / 2.8</td>
<td>V117, H18</td>
</tr>
<tr>
<td>-12-08, 03:15</td>
<td>87 / 1.9</td>
<td></td>
</tr>
<tr>
<td>-12-09, 03:00</td>
<td>47 / 2.1</td>
<td>V130</td>
</tr>
<tr>
<td>-12-11, 03:00</td>
<td>82 / 3.0</td>
<td></td>
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<td>-12-23, 03:50</td>
<td>107 / 3.1</td>
<td>V117, H18</td>
</tr>
<tr>
<td>-12-24, 03:15</td>
<td>73 / 2.6</td>
<td>V117, H18</td>
</tr>
</tbody>
</table>

Table 3 — Observation campaign parameters: Date at the mid-point of an imaging run; Exposure time in minutes / stellar FWHM in arcseconds; and variables that either were not in the field of view, or that could not be detected.
A widely quoted guide for the minimum aperture necessary for accurate uncorrected sampling is 2.5–3 times the FWHM. This guide implies, with our data, aperture radii upwards of 8 pixels would have to be used, along with a requisitely larger annular region; a sampling region of this size is illustrated in Figure 5, which shows a sampling region with a luminance filter. However, we want to obtain magnitudes that correspond (as closely as possible) to the widely-used Johnson–Cousins “$V$”-band photometric filter, so that we can make use of the calibrated PL relation, Eq. (2). Equation (4) will produce an exact $V$ magnitude for the target, with a reference star $V$-mag as input, only if the two stars have the same colour; in that case, the difference between their instrumental magnitudes will be independent of the filter used (strictly speaking, the stars must also in the same luminosity class).

Equation (4) cannot give an exact conversion from instrumental to standard magnitudes for Cepheids, using a fixed reference star, since they vary in colour with pulsation phase. Cepheid colour indices ($B – V$ magnitude differences) lie within a range of about 0.4 to 1.6 (see e.g. Ref. [21]). On the other hand, we show below that Eq. (4) produces very precise $V$-mags for the check stars, which have colour indices ranging from about 0.5 to 0.9. This strongly suggests that we will likewise obtain good approximations to the $V$-mags for the Cepheids. We present additional explicit support for this conversion procedure further down, where we estimate a so-called photometric transfer function, which can connect instrumental magnitudes for target and reference stars with different colour indices.

One of the challenges of using Cepheid variables is that they are generally found in dust lanes where the galaxy background may change rapidly within regions of small angular size. This is evident in Figure 5, which shows a sampling region with an inhomogeneous background. We initially tried to do the photometric analysis with the widely used MaxIm DL photometry tool [22], but in many cases the results were very sensitive to the size of the sampling region. Fortunately, we happened across a very powerful freeware program called Aperture Photometry Tool (APT) [23], which has many powerful features, and is very well suited to fields with inhomogeneous backgrounds. APT has an intuitive graphical user interface, can be used in interactive and batch modes, and has many tools for data visualization and analysis. For our purposes, the most important feature of APT is that it automatically generates a radial-intensity profile for the stars in an image, by sampling many unsaturated, isolated stars, and it can use the profile to correct for the flux that falls outside an aperture of a given size.

A widely quoted guide for the minimum aperture necessary for accurate uncorrected sampling is 2.5–3 times the FWHM. This guide implies, with our data, aperture radii upwards of 8 pixels would have to be used, along with a requisitely larger annular region; a sampling region of this size is illustrated in Figure 5. APT’s correction algorithm, on the other hand,
produced reliable estimates using an aperture radius of only 3 pixels. This is illustrated in Figure 6, which shows calibrated magnitudes for 2 check stars and 2 Cepheids, as functions of the aperture radius, using a fixed annulus of inner radius 5 pixels, and outer radius 6 pixels. The size of the correction depends on the image FWHM, and typically varied from around 50% for an aperture of 2 pixels, to 20% for an aperture of 3 pixels, and 5% for 5 pixels. The higher signal-to-noise that results from using smaller sampling regions is also evident in Figure 6.

We hereafter quote magnitudes estimated using an aperture radius of 3 pixels, and an annulus with inner/outer radii of 5/6 pixels respectively; the results are also insensitive to an increase in the size of the annulus.

APT also has a very convenient tool for dealing with crowded star fields, which can be used to eliminate user-selected pixels from the calculation of instrumental magnitudes. We used this tool in the analysis of V120 (located in the bottom-left quadrant of the finder image in Figure 4), which has two stars in close proximity, one of which is much brighter than the target. The APT display of the field around V120 is illustrated in Figure 7, which shows the pixels we deleted in the region occupied by the neighbouring stars. We found that the magnitude of V120 can be significantly underestimated if the background stars are not removed.

Accurate results also depend critically on the reliability of our flat-field corrections, since the sky conditions varied greatly over the course of the observing campaign; moreover, some of the target stars are relatively far from the reference stars. To assess the stability of our results, we monitored the visual magnitudes of the 5 check stars. The results for the brightest check star and the faintest, which are widely separated in the image, are plotted in Figure 8, as functions of the observation date. There is no discernable systematic change with time in any of the check-star magnitudes, within typical Poisson-noise uncertainties of about ±0.02 mag. Furthermore, our estimates of the check-star magnitudes are in good agreement with the AAVSO $V$-band values, which provides very strong support for the conversion of instrumental luminance magnitudes using Eq. (4).

We also obtained direct evidence for the reliability of our photometric conversion by measuring the transfer function for the filter that was used. This function converts the instrumental
magnitude to a calibrated magnitude in a standard filter, taking account of the different band-pases, and of the wavelength-dependent atmospheric extinction. The bandpass/extinction correction is typically parameterized by a colour index; we used the difference between the $B$-band and $V$-band magnitudes, $m_B - m_V$. A linear dependence on the index often provides a good approximation \[20\], so we considered the connection \[m_V - m_{\text{inst}} = a(m_B - m_V) + b\] (5)
The coefficient $a$ depends on the altitude at which the measurements are made, while the “offset” coefficient $b$ drops out when taking the difference between instrumental magnitudes of target and reference stars, as in Eq. (4).

We estimated the transfer function using data for reference stars in our field of view that we took from the Naval Observatory at Flagstaff Station (NOFS) database, accessed via the AAVSO freeware tool Sequplot \[24\]: we selected all available stars with uncertainties in both $m_B - m_V$ and $m_V$ of less than about 0.02 mag, yielding 9 stars with $m_V$ ranging from about 12.6–15.4 (consistent results were obtained using the standard stars in Table 2, as well as with another set of stars taken from the APASS database, via Ref. \[24\]). The colour-index dependence of the instrumental magnitudes from one night of our campaign is shown in Figure 9. The data is well described by Eq. (5), and a fit yielded $a = 0.14(5)$. Analysis of our data from other nights showed that $a$ has a negligible dependence on altitude, in the range covered during our campaign (which ran from about 50° to 80°).

We can’t actually use Eq. (5) to colour-correct our Cepheid data, since we do not have the target colour indices. However, the small value of $a$ shows that the colour corrections should be less than the typical statistical uncertainties in our instrumental magnitudes. In the case of the reference and check stars, where the differences in the respective $m_B - m_V$ values are less than about 0.2 mag, the colour corrections to the check-star $V$-mags are under about 0.03 mag. For the Cepheids, the expected colour corrections should generally be under about 0.15 mag.

V) Analysis and results

With the calibrated magnitudes in hand, our next step was to estimate the periods. Baade and Swope quote periods to three decimal places, but we cannot find how these values were obtained. A criterion that is typically used to identify candidate periods for Cepheids, which have light curves that are far from sinusoidal, is to minimize the following function of the period $P$ , often referred to as a light-curve “string length” \[25\]

$$\Theta(P) = \frac{\sum_{i=1}^{N} (m_i - \bar{m})^2}{\sum_{i=1}^{N} (m_i - \bar{m})^2} \times \frac{(N-1)}{2N}$$  (6)

where $N$ is the number of data points, $\bar{m}$ is the average magnitude, $\bar{m} = \sum_{i=1}^{N} m_i / N$ , and the data set $\{\phi_i, m_i\}$ is arranged sequentially by phase (identifying $m_{N+1} = m_1$). In general, $\Theta$ fluctuates around 1 as a function of $P$, and if no periodic behaviour is present in the data, then $\Theta \to 1$ in the limit $N \to \infty$ \[26\]. Visual inspection of the light curves is often used as an additional subjective but very effective way to discriminate among candidate periods (see e.g. Ref. \[27\]).

Figure 10 plots our result for $\Theta(P)$ in the case of H1. The rapid fluctuations over intervals of much less than one day are mainly due to noise in the data, while the deepest local minima tend to repeat in intervals of roughly 3–7 days, a pattern that is likely due to aliasing (see e.g. Ref \[26\], and for useful reviews

![Figure 9](image-url) — Transfer function for the M31 field imaged on 2017 December 8 (UT), using an ensemble of stars from the NOFS database. The instrumental magnitudes were shifted by an overall constant for clarity. The dashed line is the result of a linear fit. Error bars are dominated by uncertainties in the reference data.

![Figure 10](image-url) — String-length function $\Theta(P)$ vs. period for H1, using a step size of 0.1 days for clarity. The global minimum coincides with the B&S period of 31.38d.
of time-series analysis of light curves, see Refs. [28] and [29]). In fact, removing some of the closely spaced nights from our data set generally results in a decrease in the depth of the local minima in $\Theta(P)$, relative to the global minimum, as one would expect from aliasing in data that is sampled at irregular intervals.

We estimated the periods of all our targets by scanning for minima in their respective $\Theta(P)$ functions, using a step size of 0.01 days, as is widely employed in the literature (see e.g. Ref. [27]). In some cases, our data are too noisy to produce a clear global minimum in $\Theta(P)$, and visual inspection of the light curves, using the B&S periods to guide the search, was needed to identify candidate periods. The results of our analysis are consistent with the B&S periods to about a tenth of a day or better, with two exceptions, V54 and V66 (see the caption of Table 1 for details); we therefore adopted the B&S periods but for those two cases. Our period for V66 has the largest difference with the B&S values, although only by 0.85d. Following common practice, we do not quote uncertainties in the individual periods (cf. Refs. [26], [27]). We note however that the minima in $\Theta(P)$ have narrow widths, typically no more than a few tenths of a day, and uncertainties at that level would have a negligible effect on the absolute magnitudes obtained from Eq. (2).

We plot phased light curves in Figure 11, Figure 12, and Figure 13, with the phase $\varphi$ defined by

$$\varphi = \frac{t_{\text{obs}} - t_{\text{ref}}}{\text{Period}} + \varphi_{\text{shift}}$$

where $t_{\text{obs}}$ is the time of an observation, $t_{\text{ref}}$ is an arbitrary reference time, frac() is the fractional part of the expression in parentheses, and $\varphi_{\text{shift}}$ is an additional phase shift. We fixed the value of $t_{\text{ref}}$ in Eq. (7) to the time of maximum brightness of H1, given by the recent AAVSO study of the light curve [3]

$$t_{\text{ref}} = 2,455,430.5 \text{ Julian Days}$$

which is quoted with an uncertainty of $\pm 0.5$ days. We then determined the additional phase shifts $\varphi_{\text{shift}}$ in Eq. (7) such that the maximum brightness for each Cepheid is at zero total phase; we made rough estimates by inspecting the light curves by eye, with the results listed in Table 3. We note that the light curve for V66 is plotted twice in Figure 12, using our period, and the B&S period; the comparison shows a clear preference for our value.
After determining the periods, we computed the mean magnitudes by averaging over intensities, employing the widely used definition [30]

\[
\langle m \rangle = -2.5 \log_{10} \sum_{i=1}^{N} 0.5(\varphi_i + 1 - \varphi_i - 1) 10^{-0.4m_i}
\]

with the identification \(\varphi_{N+1} = 1 + \varphi_1\) and \(\varphi_0 = \varphi_N - 1\); the phase difference factor gives greater weight to data that are more spread apart in phase over data more closely bunched together. Results for the mean magnitudes are given in Table 3.

Figure 14 plots the mean magnitude versus the period. This plot is one of the major highlights of this work, as it clearly reproduces Leavitt’s period-luminosity relation, given that the Cepheids are at approximately the same distance. This is a very dramatic “rediscovery”!

After our analysis was complete, we found that the mean magnitudes of seven of our targets could be extracted from a plot in the paper by Freedman and Madore (F&M) [17] (numerical values are not given); our results are in agreement to within our Poisson-noise uncertainties in all of these cases, which include both the shortest- and the longest-period variables in our data set, V146 and V120, respectively.

To estimate the distance, we first estimated the apparent distance modulus \(m_{\text{app}}\) from a fit to

\[
\langle m_\nu \rangle = \langle M_\nu \rangle + m_{\text{app}}
\]

which amounts to a vertical shift in a line of fixed slope, as illustrated in Figure 14. We found \(m_{\text{app}} = 24.98(9)\), unweighted by the errors in the mean magnitudes. This is in excellent agreement with F&M, who obtained \(m_{\text{app}} = 24.99(8)\) [17], after correcting for a small difference in the zero-point of the PL relation that they used, compared with Eq. (2). The standard error in our value of \(m_{\text{app}}\) corresponds to an RMS dispersion of 0.38 in the fit, which is illustrated in Figure 14, and reflects the inherent dispersion in the PL relation (cf. Figure 3), inflated by Poisson-noise fluctuations in our mean magnitudes.

We note that if we take the slope in the PL relation to be a free parameter, the fit returns an absolute value that is appreciably smaller than in Eq. (2). This is very likely due to a bias in our sample toward more-luminous shorter-period Cepheids, which is supported by the results of F&M, who measured several fainter targets than we could reach; other studies commonly fix the slope in order to avoid a similar bias (see e.g. Ref. [31]).

To obtain the true distance modulus \(\mu\), one must take account of extinction due to interstellar dust along the line of sight, through the Milky Way and into the target galaxy. The magnitude shift owing to extinction in a wavelength band \(X\) is denoted by \(A_\nu\), so here we write

\[
\mu_{\text{app}} = \mu + A_\nu
\]

F&M estimated extinctions in the B&S fields by measuring the apparent distance moduli in several band-passes, and fitting the differences with a model of extinction due to galactic dust; they found \(A_\nu = 0.61(12)\) for B&S Field I.

The uncertainty in our estimate of the true distance modulus is dominated by the systematic uncertainty in the photometric conversion from instrumental magnitudes, which we estimated in Sect. IV to be less than about \(\pm 0.15\) mag, along with the uncertainty in the extinction. We add these systematic errors in quadrature with the standard error in the fit to Eq. (10).

Our final result is \(\mu = 24.37(21)\). This is in excellent agreement with a recent analysis of many studies of the distance to M31 [32], which recommends a robust mean value of 24.46(10).

With the distance in parsecs given by

\[
d(\text{pc}) = 10^{(m_{\text{app}} + 5)}
\]

our estimate of the distance to M31 is 0.748(76) Mpc, or 2.44(25) million light-years.
VI) Summary and outlook

We succeeded in reproducing Leavitt’s Law from observations of 17 Cepheid variable stars in M31, over a two-year campaign. The precision of the magnitude estimates was enhanced by imaging with a luminance filter, and carefully validating a straightforward but precise photometric conversion to the standard V-band. By comparing with a widely used calibration of the PL relation, and taking account of interstellar extinction along the line of sight, we obtained an estimate of the distance to M31 with an uncertainty of 10%, and in agreement with the known value.

Other projects along these lines could include studying Cepheids in other regions of M31, and in the few other members of the local group of galaxies that are accessible to smaller telescopes, the Triangulum Galaxy M33 being a notable case [33]. A particularly interesting project would be to independently estimate the extinction due to galactic dust, although this would require imaging through at least two standard band-passes (e.g. B- and V-bands), which would have significantly smaller signal-to-noise levels relative to luminance images.

References

Throwback to the glorious Comet Hale-Bopp from 1997. Luca Vanzella said, “I drove through a snowstorm to a country road north of Edmonton and got this shot—on Fuji film. I have shots that show more of the comet, but this one represents the naked-eye view best. Scanned negative and curved a bit in GIMP.” The 20-second image was taken north of Gibbons, Alberta, on a Canon A-1, f/2.8, 50-mm, Fuji 800 film. Even though Luca shot in colour, the subject displays very nicely when converted to a greyscale image. This image was one that Luca supplied for his Astrophotography Certificate submission in the Wide Field category. See rasc.ca/astro-imaging-certificate See also all the submitted entries from when the program began in 2016 at rascastroimaging.zenfolio.com
Kerry-Ann Leeky Hepburn photographed the Milky Way from Grampians, Victoria in Australia. This is a single cropped image she shot using a Canon 6d, at ISO 6400 using a Sigma 14mm lens at f/1.8 and 25 sec.