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Determination of the distance to the Andromeda Galaxy using variable stars

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6 The distance to M 31 and final remarks

During the course of the present work, several distance determinations to M 31 have been obtained. In order to study the relationship between the derived distances and to place the derived values in context, a brief discussion is required (Sect. 6.1). Once the final distance is derived and placed in context, the results derived in the present work are summarized (Sect. 6.2) together with some comments on future investigation lines that could help to improve the presented results (Sect. 6.3).

6.1 The distance to M 31

From the results given in Sect. 4.2, it is obvious that the main goal of the present work (a direct and accurate distance determination to M 31 from EBs) has been fulfilled. The derived distance modulus of $(m - M)_0 = 24.36 \pm 0.08$ mag relies on the modeling of two different EBs and, therefore, can be considered to be:

- *Direct*. The distance determination from EBs does not rely on previous calibrations and, since it is derived using a one-step procedure, it can be considered direct. Therefore, a posterior recalibration of the distance to other Local Group galaxies (such as LMC) or a variation on the zero-point of any standard candle (such as Cepheids) has no effect on the derived distance. Furthermore, any standard candle in M 31 can be calibrated using our derived distance.
- *Accurate*. One of the most important points when determining distances is the effect of possible systematics in the derived value. Contrary to other distance determinations, the uncertainty in our distance modulus includes most, if not all, the possible systematics. In particular, the possible sources

of systematic errors, and the corresponding considerations, can be summarized in the following points:

- Photometry. The photometry has been compared with other catalogs (Sect. 2.3.1) and checked to be well below 0.03 mag for the magnitude of the selected EBs.
- Assumed configuration in the modeling of the EBs. The configuration assumed is completely independent for each one of the two EBs used for distance determination and result in distances that agree within the uncertainties. In addition, SB2A has clear evidences of being a post-mass-transfer EB (O'Connell effect, no eccentricity, secondary apparently more evolved, etc.) and SB2B has been thoroughly tested for any other possible configuration, with none of them being capable to reproduce the observations.
- Radial velocities. Several aspects have been considered with respect to the radial velocity determinations. TODCOR is a well tested program that has been checked to introduce some systematics only for spectra with a short wavelength coverage (Torres & Ribas, 2002), which is not our case. In addition, the possible systematics introduced by the use of Balmer lines (that can be affected by stellar winds) is compensated with the incorporation of He lines. In addition, the stellar wind would introduce a bias mainly in the systemic velocity, which has no impact in the final distance determination.
- Stellar atmosphere models used to determine the surface flux. This is probably the major source of systematic errors, since it is based on several calibrations. However, the models used are thoroughly tested in several branches of astronomy. In addition, the derived fluxes are compatible with the HST spectrophotometry at optical wavelengths. Therefore, any possible systematics are expected to be well below 0.05 mag.
- Line-of-sight absorption. As seen in the spectrophotometry, the ultraviolet part of the mean galactic extinction curve is unable to reproduce the observed values. However, the only effect in the determination of the absorption at optical wavelengths would be a variation in the determination of $\mathcal{R}_V$. The value of $\mathcal{R}_V$ has already been considered to have an uncertainty of 10% and larger variations are unlikely, as seen from previous statistical analysis (Fitzpatrick & Massa, 2007).

• *Precise*. The uncertainty on the derived distance modulus of 0.08 mag represents a distance determination with an error of only 4%. Although several of the values reported in Table 1.1 have smaller errors, most of these results do not consider the effect of systematics. In fact, the derived uncertainty is equal to the standard deviation resulting from the combination of all the non-direct distance determinations in Table 1.1 and, therefore, our derived distance is equally precise.

Therefore, EBs have proven to be excellent distance markers and, arguably, the best method to provide direct distances for all the galaxies in the Local Group.

The uncertainty in the derived distance could be improved with the analysis of additional EBs (already identified in the list of 24 EBs provided in Sect. 2.4.1), resulting in a distance determination to M31 with a relative uncertainty of 2–3% and free of most systematic errors. This result would represent the most accurate and reliable distance determination to this important Local Group galaxy. In addition, a better determination of the line-of-sight absorption could also improve the uncertainty in the distance determination. In this sense, observations (already performed) with GALEX (Thilker et al., 2005) and Spitzer (Mould et al., 2008) could help to determine the spectral energy distribution of the observed EBs and, therefore, to better constrain the absorption.

The derived distance modulus is in complete agreement with the mean value in Table 1.1 (Fig. 6.1). In fact, *all* the 18 distances reported in Table 1.1 agree with the EB value within 2σ and prove that the different distance indicators are all rather well calibrated within their error bars. In addition, the large number of distance indicators observed in M 31 strengthens the importance of this galaxy as the main calibrator for extragalactic distance determinations. In fact, all the distance indicators used to determine a distance to LMC (Gibson, 2000), can be used, in principle, in M 31. In addition, at least two other distance determination methods can be used in M 31 (planetary nebulae luminosity function and Tully-Fisher relationship). Therefore, after the direct distance obtained with EBs, M 31 may be the best extragalactic benchmark for distance determinations.

Cepheids have also been used to determine a distance to M 31 (Sect. 5.4). The derived distance modulus of $(m - M)_0 = 24.32 \pm 0.12$ mag represents an additional distance determination to M 31 that is fully compatible with the EB value. The consistent result with EBs proves that the Cepheid analysis performed, including the period-luminosity relationship, metallicity correction and blending, is correct (within the uncertainties). The consistency of the results is specially valuable, because the EB distance to LMC has been used as reference. Therefore, the Cepheid distance modulus proves that the EB distances to LMC and to M 31 are fully compatible, tightening the extragalactic distance scale.

In fact, Cepheids have proven to be extremely useful and robust to determine *relative* distances among galaxies. Macri et al. (2006) used the Cepheids in NGC 4258, which has a direct maser-based distance (Herrnstein et al., 1999), to determine a distance modulus to LMC that is almost identical to the EB value. Therefore, the derived distances using EBs are not only fully compatible among themselves, but also to other direct distance determination methods.

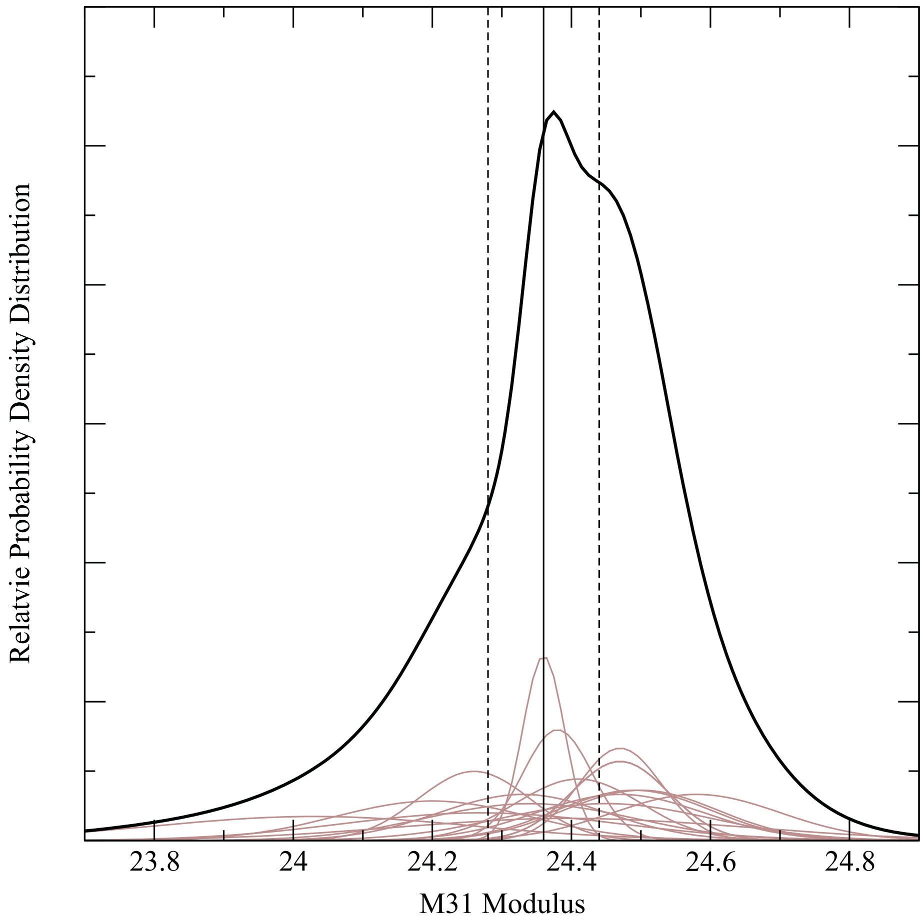

Figure 6.1. Distribution of M 31 distance moduli as compiled in Table 1.1 plotted as a continuous probability density distribution (black line) built from the sum of individual unit-area Gaussians centered at the quoted modulus, and broadened by the published internal random error (gray lines). Distance to M 31 derived after the present work is shown (straight black line) together with its 1σ error bars (dashed lines).

6.2 Summary of the results

The main results of this work are summarized here to enable a quick look. For any additional information in a specific topic, see the corresponding section.

6.2.1 Data acquisition, reduction and analysis

As the very first step in the determination of a distance to M 31, deep and high-quality time-series photometry was obtained. A region (of $33'.8 \times 33'.8$) in the north-eastern quadrant of M 31 was observed during five years in *B* and *V* with the WFC at INT. Two main factors place the present survey among the best variability surveys obtained so far in M 31. On one hand, the implementation of the image subtraction technique has allowed the acquisition of highly precise photometry (∼ 0.01 mag at $V \sim 19$ mag) of 3 964 variable stars, with 437 EBs and 416 Cepheids. This technique is representing a revolution in the search for extragalactic variable stars, where crowding is a major concern, being also implemented with great success in other surveys as OGLE (Udalski et al., 2008) or DIRECT (Mochejska et al., 2001b). On the other hand, the great number of observations (∼ 250 per passband) has enabled an almost complete coverage of the light curves of all the variables with periods shorter than five days.

In addition to the photometry of variable stars, photometry of all the detected stars in the field of view (236 238) was also obtained. The resulting photometry is both precise (with 37 241 objects having errors below 0.1 mag in B and V) and accurate, since it has been checked for compatibility with other surveys, such as LGGS (Massey et al., 2006) and DIRECT (Macri, 2004). The comparison has revealed that any possible systematics larger than 0.03 mag for the brightest stars can be ruled out. In addition, it is one of the deepest photometric surveys obtained in the disk of M 31 (with magnitude limits at $V \simeq 25.5$ and $B \simeq 26.0$). Therefore, our resulting catalog can be used as a reference to extend the time baseline of future stellar surveys in M 31.

Apart from the already identified population, there are over 3 000 variable stars still pending for an identification. The obtained catalog can contain any type of variable stars (Miras, LBVs, etc.). In fact, one of the variable stars (M31V J00441943+4122468) is a well known LBV (V15, King et al., 1998). Therefore, the obtained catalog represents an important database for future studies in M 31. The great potential of the obtained catalog to analyze additional variable stars has been revealed by the discovery of a dM4 flaring star in the Milky Way (Appendix A). Therefore, further analysis on the already obtained data could reveal other interesting objects in M 31 and in our own galaxy.

Another requirement to derive a distance determination to M 31 with EBs is the acquisition of spectroscopy. The EB sample was inspected in order to identify those systems that were more suitable for accurately determining the components' physical properties. A list of 24 EBs was selected to be the best candidates for spectroscopic follow up and multi-object spectroscopy was obtained for five of them. The observed sample is only a small fraction of the total number of selected EBs. Therefore, the list provided constitutes an excellent masterlist from which to select EB systems for further observations.

The nine spectra per target acquired with GMOS at Gemini-North have a resolution of ∼ 80 km s^{-1}, cover the wavelength interval of ∼ 380 nm to ∼ 530 nm (with most of the Balmer lines) and have a S/N ranging from 5 to 40. EBs have a major drawback when obtaining radial velocities, since their relatively short orbital periods preclude the use of long exposure times, thus limiting the

S/N. However, the techniques used in the course of the present work (with the implementation of TODCOR, TIRAVEL, TRIMOR and KOREL) have enabled the determination of radial velocities, even for low S/N spectra. In addition to the acquisition of radial velocities, the techniques used have enabled the disentangling and the combination of the observed spectra to produce a higher S/N spectrum. The great similarities of the obtained spectra with synthetic counterparts reveal that spectral disentangling is capable to provide accurate fundamental properties for the individual components of EB systems even for low S/N spectra. Therefore, the techniques applied during the course of the present work clearly reveal that fundamental properties of EB systems in Local Group galaxies can be obtained with current facilities.

Finally, the obtained spectrophotometry (with ACS at HST) has revealed that current instrumentation has to be improved in order to derive precise spectrophotometry for stars in M 31. This instrumentation existed in the past (i.e., STIS and FOS), but the current state of HST has reduced the capability to obtain precise spectrophotometry of faint stars. Hopefully, the situation will change in the near future, with the Service Mission 4 to HST in 2009 and the launch of the World Space Observatory/Ultraviolet in few years. These two space missions should provide new instrumentation in the ultraviolet to the scientific community, which should enable the acquisition of precise spectrophotometry of faint stars and, thus, allow the use of the spectrophotometric method for EBs in M 31 (and other galaxies in the Local Group).

6.2.2 Properties of eclipsing binaries

The determination of the fundamental properties of bright stars in other galaxies has revealed to be a valuable source for identifying massive stars (e.g., Bonanos et al., 2004). The comparison of the color-magnitude diagrams of EBs (Fig. 2.10) and Cepheids (Fig. 2.12) has revealed that the EB population observed is much bluer ($< B-V >= 0.1 \pm 0.5$) than the Cepheid population ($< B-V >= 0.9 \pm 0.3$). Considering the mean blending-free color excess derived of $< E(B-V) >= 0.305 \pm 0.011$ (Sect. 5.3.3), the reddening-free mean color of the EB population is $< B-V >= -0.2 \pm 0.5$. Therefore, most of the reported EB systems are composed by blue and massive main sequence components.

EBs are excellent tools to determine fundamental properties of massive stars in M 31 and other Local Group galaxies. Direct determinations of masses and radii for massive stars in the Milky Way are more difficult due to absorption. Therefore, extragalactic determinations of masses and radii (like the ones performed in the present work) will greatly help in determining the fundamental properties of the most massive stars. The analysis of four EBs in Chap. 4 (with two double-line, one single-line and one triple-line EB) has revealed a whole zoo of different massive stars, all of them being extremely interesting to better understand the physics of these stars.

The modeling of the double-line EBs has provided masses and radii with relative uncertainties below 10% and around 5%, respectively, which is remarkable given the faintness of the stars. Although both systems have similar components (with masses around 22 $M_\odot$ and 15 $M_\odot$), the evolutionary stage of each EB is largely different. SB2A (M31V J00443799+4129236) is a semi-detached EB with active mass transfer, where the originally more massive component is now observed as the secondary. The observed O'Connell effect in SB2A can well be used, in the future, to infer the mass transfer rate in such a massive binary system. SB2B (M31V J00443610+4129194), on the contrary, is a pre-mass-transfer EB (with an age of about 4.2 Myr), where the more massive component is about to fill its Roche lobe. This evolutionary stage is not commonly observed in massive EBs, due to the short time spent at this stage. Therefore, both systems have characteristics that make them interesting cases of close EBs, enabling futures studies of mass transfer and the effects of proximity on the evolution of massive stars.

In the case of the single-line EB (M31V J00444528+4128000, SB1), two evolved and massive components (of ~26 $M_\odot$ and ~14 $M_\odot$) have been observed. The analysis performed has revealed that the primary component is a blue supergiant in a semi-detached configuration. This system can be useful to study the mass transfer of massive stars during the helium burning phase.

Another interesting target is the triple-line EB (M31V J00442326+4127082, SB3). This target is composed by two extremely massive stars (49 $M_\odot$ and 46 $M_\odot$) with an age of 2.3 Myr. The measured apsidal motion of $\dot{\omega} = 2.4 \pm 1.0$ deg year^{-1} identifies this system as the most massive EB with apsidal motion ever reported. The analysis performed so far has revealed the great value of this EB to study and verify the stellar interior models for stars with convective core. Further analysis of the obtained data should help to verify whether the observed stars have convective envelopes larger than those predicted by stellar models. In this sense, since the photometric survey ended in 2003, current observations of SB3 would already be able to greatly improve the apsidal motion rate determination.

The obtained results open the field of detailed investigations of stellar evolutionary models for massive stars (single and binary) in another galaxy and, hence, in a completely independent chemical environment. It is important to remind that only four of a list of 24 massive EBs have been analyzed. The analysis of additional EBs in the list could provide an excellent workbench where to test stellar structure and evolutionary models. However, the analysis of the reported sample involves the acquisition of spectra with large telescopes (8–10 m) having spectroscopic instrumentation in the optical. Currently, one of the only telescopes with such facilities in the northern hemisphere is Gemini-North. Fortunately, Gran Telescopio de Canarias (GTC) has just started operations with OSIRIS, an instrument that could well be suitable for this study when the proper gratings are available.

6.2.3 Properties of Cepheids

The large number of detected Cepheids (416) motivated a comprehensive analysis of the Cepheid population in M 31. Having the same number of Cepheids that the General Catalog of Variable Stars, our catalog is much deeper, being almost as complete as the David Dunlap Observatory Milky Way sample. Both period distributions have a double-peak structure, with a dip at around 10 days. The only difference may be the lack of long period (and bright) Cepheids in our catalog.

In addition, the large number of epochs obtained (~ 250) in both filters (*B* and *V*) has permitted the accurate pulsation mode identification of 240 fundamental mode (FM) and 75 first overtone (FO) Cepheids. The sample of FM Cepheids was completed with 41 long period (i.e., longer than 8 days) Cepheid variables, resulting in a total amount of 281 FM Cepheids. The subsequent analysis of this sample revealed that at least three of these stars are, in fact, type II Cepheids. Regarding FO pulsators, although some FO Cepheids were previously detected in M 31 (Fliri et al., 2006), our sample yields an important increase in the number of detected FO pulsators and opens a new window to study the basic properties of these stars in another Local Group galaxy.

The analysis of the P-L relationship for the FM Cepheids reveals a large scatter, which is not explained solely through the effects of interstellar absorption and metallicity. Although additional efforts are needed to reduce the obtained uncertainties, a new method to compute the effect of blending was developed. The exact dependence of the amplitudes among different passbands, as well as more precise amplitude determinations, would greatly enlarge the results shown here. The uncertainties could also be reduced by acquiring time series photometry at longer wavelength (such at *I* band or at the infrared).

Even by considering the large uncertainties, the large number of studied Cepheids provides an accurate characterization of the mean blending values, which are in good agreement with those derived by Mochejska et al. (2000, 2004) in M 31 and M33. We conclude that the most likely cause of blending seems to be the light from unresolved stars belonging to the same stellar associations or clusters as Cepheid variables.

The effect of blending has also been shown to be larger than 0.09 mag in the distance modulus to M 31, thus having an effect as important as the metallicity correction. Therefore, blending should always be taken into account when obtaining extragalactic distance determinations with Cepheids.

6.2.4 Distance determinations

Four distance determinations to M 31 have been presented in the course this work. Of these, two are direct distance determinations with EBs, deriving distance moduli of $(m-M)_0 = 24.44 \pm 0.12$ mag and $(m-M)_0 = 24.30 \pm 0.11$ mag. These values have been averaged to derive a robust distance modulus to M 31 of $(m - M)_0 = 24.36 \pm 0.08$ mag, firmly establishing the distance to this important galaxy. Another EB has been shown to provide a distance determination to M 31 of $(m - M)_0 = 24.8 \pm 0.6$ mag. This value cannot be considered a direct distance determination because stellar evolution models were used. The derived distance, however, represents a useful cross-check to ensure that the properties derived for this binary, composed of extremely massive stars, are consistent. Finally, the Cepheids identified in the photometric catalog have provided a distance to M 31 of $(m - M)_0 = 24.32 \pm 0.12$ mag. The derived value is fully compatible with the EB distance determinations, providing an additional check on the derived results.

6.3 Future work

As the last step in the present work, some comments are made on how to improve the derived results. Most of them have already been mentioned somewhere else in the course of the present work. Even though, they are placed together here for reference.

The extensive data analysis performed in the course of the present work has provided a wealth of data acquired with leading observational facilities. Our investigation was centered on acquiring the necessary information to derive a distance to M 31, setting apart any additional information. Therefore, the obtained data can be an excellent starting point for future work.

One of the potential sources for future analysis is the photometric catalog of variable stars (Sect. 2.3.2). Of the derived sample of 3 964 variable stars, there are over 3 000 sources still pending to be identified. The possible sources in the compiled catalog are numerous, and range from luminous blue variables (M31V J00441943+4122468) to flaring stars in the Milky Way (see Appendix A) with, probably, several long period variables (like Miras).

Another source for future work is the list of 24 EB selected as suitable candidates for distance determination (Sect. 2.4.1). Four EBs have been analyzed in the course of the present work. Therefore, there are still 20s EB waiting for spectroscopic observations. The future analysis of the sample can result in a distance determination to M 31 with a relative uncertainty of 2–3% and free of most systematic errors.

In addition to the distance determination, the analysis of the EB sample would provide an excellent benchmark where to test stellar structure and evolutionary models. In particular, the EB sample could be used to determine internal structure constants through the apsidal motion (e.g., SB3 in Sect. 4.1.4), to study the mass transfer in semi-detached systems (e.g., with SB2A in Sect. 4.1.1) or, since the radii of stars can be directly determined, to study the wind momentum-luminosity relationship for massive stars (see Kudritzki & Puls, 2000, for a review).

Apart from EBs, the present study has shown that accurate photometry for Cepheids in M 31 can be obtained. A program to obtain high quality light curves in whole disk of M 31 would be of great interest. The presented work has revealed hundreds of Cepheids in a region that is about one third of the M 31 disk. Therefore a specially aimed survey (with *I* photometry) could reveal several thousands of Cepheids in this galaxy. In fact, the determination of the global properties of Cepheids (such as the period distribution or the dependence on metallicity) could be much more easy to study in M 31 than in our own galaxy.

Another interesting project would be the analysis of blending in other Local Group galaxies (and beyond) using the method presented in this work. The method needs high accuracy light curves ($\sim 0.01 - 0.02$ mag) with a large number of epochs (~ 100). The only galaxies currently having these light curves are LMC, SMC, the Milky Way and M 31. All the galaxies quoted (except M 31) are expected to have low blending values. Considering that blending can be as important as metallicity correction for the final distance determination with Cepheids, further investigations in other Local Group galaxies would be extremely valuable.