

Numerical Techniques and Histories of Galactic dSph Companions

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Abstract. I present star formation histories (SFHs) of seven galactic dwarf spheroidal companions: Carina, Draco, Leo I, Leo II, Sculptor, Sagittarius, and Ursa Minor. The data are limited to WFPC2 images, which provide a diverse sample of conditions (number of stars, foreground contamination, young vs. old stars, etc.) under which numerical techniques can be examined.

1. Background

With a wide variety of star formation history (SFH) reconstruction algorithms in use, it is worthwhile to make a careful study of how accurately these techniques can determine SFHs. While questions of isochrone accuracy are clearly critical in this field, they are addressed by other papers in this volume. I will focus on the SFH solutions themselves, examining how well the observed color-magnitude diagram (CMD) can be reconstructed and how large the regimes of “acceptable” solutions are under a variety of conditions.

WFPC2 observations of galactic dwarf spheroidal companions provide an ideal test for such an exercise, as a wide range of CMD conditions and qualities is sampled. Four of the seven that have been observed (Draco, Leo II, Sculptor, Ursa Minor) show primarily-ancient (> 5 Gyr) star formation; three (Carina, Leo I, Sagittarius) have significant amounts of young stars. Two (Leo I and II) are significantly more distant than the others and thus contain large amounts of stars; one (Sculptor) was observed near the edge of the galaxy and thus has quite few. Two (Carina and Sagittarius) have significant amounts of foreground contamination that obscure the RGB.

Some notes are in order regarding my SFH-measuring algorithm should be given here, although the reader is directed to Dolphin (2002) for details. I use “noiseless” synthetic CMDs, in that all phases of stellar evolution at all metallicities and all ages are taken into account, combined with all possible artificial star results. Foreground stars and false detections are also included in the synthetic CMD. This produces a true “model” CMD, representative of the theoretical distribution from which the observed data would be drawn (if the SFH being tested is correct). The statistic of choice is a Poisson maximum likelihood ratio, which is superior to χ^2 for Poisson-distributed data (a χ^2 minimization will *always* produce the wrong answer). Based on the number of free parameters in the solution, a regime of “acceptable” solutions surrounding the best solution is

determined; this is used to determine the error bars. It should also be noted that I make as we *a priori* assumptions as possible. The SFH is solved as a function of both age and metallicity, and both distance and extinction are solved.

All seven galaxies were analyzed in a homogeneous manner. Public data were obtained from the Hubble Space Telescope archive using OTFC. The photometry was made using HSTphot (Dolphin 2000a) and calibrated using an updated version of Dolphin’s (2000b) CTE/calibration solution. SFHs were then measured using metallicity limits of $-2.4 < [M/H] < +0.1$ and age resolution of 0.15 dex. In order to test how well CMD analysis can measure star formation histories (as well as distance and extinction), no “outside” information (such as distance, metallicity, or extinction) was used.

The reader is referred to Dolphin (2002), which gives not only a detailed description of the SFH measurement procedure, but more information about each of the galaxies (literature values, CMDs of all objects, other empirical measurements from these CMDs, star formation rates and chemical enrichment histories, etc.) that was omitted from this paper for the sake of brevity.

2. Galaxies

2.1. Leo II

Leo II serves as the best-case galaxy in this study, as it is primarily-old and contains many stars. The photometry contained 12642 stars (5188 of which are brighter than $M_V = +4$ and are thus useful in measuring the SFH). A broad turnoff region indicates that Leo II has a significant age spread. A measurement of the HB mean magnitude indicates a distance modulus of $\mu_0 = 21.67 \pm 0.10$, using the calibration of Carretta et al. (2000).

The fitting algorithm returned a solution consistent at the 2.15σ level, which is moderate. The distance modulus and extinction were measured to be $\mu_0 = 21.55 \pm 0.08$ and $A_V = -0.04 \pm 0.09$, both values consistent with those in the literature and given above. Clearly a negative extinction is unphysical; however A_V was allowed to vary freely to adequately minimize the fit parameter.

I find a significant amount of star formation from 6 Gyr ago until 15 Gyr ago, at a constant level of star formation. There has been little star formation since then, although there is a 1.75σ detection of some star formation between 2 and 4 Gyr ago. This SFH is consistent with the SFH recovered by Mighell & Rich (1996), but is more extended and older than that found by Hernandez et al. (2000). It should be noted that the younger history measured by Hernandez et al. (2000) cannot create the observed blue HB; thus some amount of older stars is necessary. The mean metallicity is found to be $[M/H] = -1.19 \pm 0.20$, which is consistent with the measurement of Mighell & Rich (1996), after accounting for differences in the metallicity scales and age effects on RGB color.

2.2. Draco

The Draco dwarf spheroidal is another predominantly-old object, but its shorter distance means that WFPC2 covered less of the galaxy. As a result, the CMD contains only 5.5% the number of evolved stars as was present in Leo II. Also adding to the difficulty is the fact that stars within half of a magnitude of the

RGB tip would have been saturated; thus a small amount of information is lost. No evidence of intermediate-age stars is apparent in Draco's CMD. Based on the HB mean magnitude, the distance modulus is $\mu_0 = 19.60 \pm 0.18$.

The CMD fit returned a solution consistent at the 1.43σ level (which is rather good). Acceptable fits were found with distance and extinction values of $\mu_0 = 19.49 \pm 0.11$ and $A_V = 0.28 \pm 0.08$, respectively. While the distance is within the error bars of the values from the literature and from the HB in this data, the large extinction (also seen in the RGB color and thus not a solution error) could imply a zero point error in the photometry. This is quite possible, given that F606W was used instead of the standard F555W.

The star formation rate was found to be consistent with zero everywhere except 11 – 15 Gyr old stars, which have a mean metallicity -1.85 ± 0.4 . There is a possibility of a significant amount of star formation (more than the lifetime average rate) lasting until 8 Gyr ago, but very little since then. This conclusion of an entirely ancient galaxy is consistent with that determined by Carney & Seitzer (1986) and Grillmair et al. (1998).

2.3. Ursa Minor

Ursa Minor represents another step down in terms of the number of evolved stars in the CMD (3.3% the number of Leo II). As with Draco, any stars at the RGB tip would have been saturated; however this is only a minimal loss of information. As with Draco, the CMD shows a very narrow turnoff and thus no evidence of stars younger than globular cluster ages. The distance modulus calculated from the HB mean magnitude is $\mu_0 = 19.28 \pm 0.25$, the large uncertainty resulting from using a small number of HB stars.

The fit to Ursa Minor's CMD was consistent at the 0.91σ level (which is very good). The distance and extinction, as constrained by fit quality, were measured to be $\mu_0 = 19.16 \pm 0.11$ and $A_V = 0.12 \pm 0.09$, respectively, both values consistent with literature values and the HB distance above.

The star formation rate was again consistent with zero at all ages younger than 11 Gyr, with a mean metallicity of $[M/H] = -1.53 \pm 0.29$ for ancient stars. Again, it is possible for significant star formation to have been present as young as 8 Gyr ago, although there is no evidence to suggest that. This conclusion of an entirely ancient galaxy is consistent with the histories of Olszewski & Aaronson (1985), Mighell & Burke (1999), and Hernandez et al. (2000).

2.4. Sculptor

The extreme case, in terms of numbers of stars, is that of the Sculptor dwarf spheroidal. The Sculptor CMD contains only 46 stars with $M_V < +4$, which is 0.9 % the number observed in Leo II. Additionally, because no short exposures were taken, any stars brighter than $M_V = 0$ would have been saturated, and the CMD is thus missing the upper RGB. The Sculptor CMD shows no evidence of old stars, although so few stars of any kind are present that a definitive claim is impossible from these data.

As with Ursa Minor, a very good fit to the CMD (consistent at the 0.31σ level) was achieved. The distance modulus and extinction were measured to be $\mu_0 = 19.45 \pm 0.31$ and $A_V = 0.06 \pm 0.19$, respectively, both values consistent with literature values (though with very large error bars).

The best-fit SFH was nearly identical to that measured for Ursa Minor: all ancient stars, with a mean metallicity of $[M/H] = -1.54 \pm 0.72$. However, the very small number of stars in the CMD prevented a unique solution; indeed the star formation rate could be increased to the lifetime average for any period in the galaxy’s history without sufficiently changing the CMD. This conclusion of an entirely ancient galaxy is consistent with that obtained by Monkiewicz et al. (1999) as well as the ground-based work of Da Costa (1984).

2.5. Leo I

Leo I adds another level of complexity to this problem, as it contains a very strong young population that dominates the CMD. Fortunately its CMD contains more stars than the other galaxies (31064, of which 22290 have $M_V \leq +4$), making a reconstruction possible. The saturation and faint-end cutoffs are sufficient to include all evolved stars. The CMD shows an extremely broad turnoff, with some main sequence stars seen slightly brighter than the horizontal branch. The red clump, using the technique described by Dolphin et al. (2001), produces a distance of $\mu_0 = 21.81 \pm 0.14$, while an RGB tip distance, assuming $M_I = -4.00 \pm 0.05$, produces $\mu_0 = 21.87 \pm 0.19$.

The quality of the CMD fit was the worst of all objects, consistent only at a 7.47σ level. This is not surprising, since that the SFH appears to have been extremely bursty; therefore the broad binning of $\Delta \log t = 0.15$ in the solutions was likely unable to adequately match the CMD. For Leo I, I measured a distance modulus of $\mu_0 = 21.80 \pm 0.06$ and an extinction of $A_V = 0.04 \pm 0.05$; both values are consistent with those in the literature and derived from the CMD.

The SFH of Leo I is unlike that of any of the previous galaxies, with a rate the highest between 1 and 8 Gyr ago and a very strong burst between 2 – 3 Gyr ago. Leo I also contains a significant amount of ancient stars (a 1.4σ detection of stars older than 11 Gyr), as well as a small amount of stars formed as recently as 0.5 Gyr ago. The mean metallicity is seen to be $[M/H] = -1.02 \pm 0.14$, with very little enrichment over time. (It increases from $[M/H] = -1.12 \pm 0.16$ older than 8 Gyr ago to -0.84 ± 0.12 in the past 2 Gyr.) The star formation history is broadly consistent with previous studies that used these data (Gallart et al. 1999; Hernandez et al. 2000). The $> 1\sigma$ detection of ancient stars agrees with the results of NTT observations made by Held et al. (2000).

2.6. Carina

The Carina dwarf spheroidal also contains relatively young stars. While its young population is not as dominant as that of Leo I, it was much more difficult to analyze because of a much smaller number of stars in the CMD (3.3% that found in Leo I) as well as being the first object in this study that contains a significant number of foreground stars. Carina’s main sequence turnoff region is extremely broad, reaching about 1 magnitude below the horizontal branch. This is a clear signal of extended star formation, though not to the extreme degree seen in Leo I. An HB distance (based on three stars) is $\mu_0 = 20.01 \pm 0.29$, while the red clump distance is $\mu_0 = 19.90 \pm 0.20$.

The CMD fit consistent at the 2.03σ level, which is a moderate fit. The distance modulus and extinction were measured to be $\mu_0 = 20.19 \pm 0.13$ and $A_V = -0.04 \pm 0.14$, respectively, giving it a longer distance but smaller reddening

than literature values. The reason for this incorrect solution is the presence of foreground stars, which partially wash out the red giant branch. As the main sequence was not very well-measured below the turnoffs, there was very little color-sensitive information in the CMD.

The SFH shows significant amounts of star formation from 15 Gyr ago until 2 Gyr ago. There is possible evidence of two bursts from 2 – 4 Gyr ago and from 6 – 11 Gyr ago, though this is only a 1σ detection. This result agrees very well with the ground-based study of Hurley-Keller et al. (1998). The WFPC2 study of Mighell (1997) finds no stars younger than 4 Gyr (which is ruled out here), while that of Hernandez et al. (2000) finds no stars older than 10 Gyr (which is ruled out by the presence of blue HB stars in the ground-based CMD of Smecker-Hane et al. 1994).

2.7. Sagittarius

The final galaxy to be examined is the Sagittarius dwarf spheroidal, whose CMD contains a similar number of evolved stars as Carina, but with much worse foreground contamination. However, the data provide an excellent main sequence, which can be used to help constrain the distance and extinction and thus avoid the problems encountered in the Carina data. The data consist of two pointings; one near the center and one 2.4° away. The two CMDs were analyzed separately because of the possibility of differences in extinction and SFH. Both show broad turnoff regions, with the central field CMD similar to Carina and the outer field CMD showing fewer young stars. Because of the severe foreground contamination, no distance can be obtained from the CMD.

Both CMDs were fit extremely well: the inner field was consistent at the 1.19σ level and the outer field at the $< 0\sigma$ level. The distance modulus and extinction were measured to be $\mu_0 = 17.11 \pm 0.14$ and $A_V = 0.46 \pm 0.11$, respectively, in the central field, and $\mu_0 = 17.09 \pm 0.17$ and $A_V = 0.45 \pm 0.13$ in the outer field. These are consistent with literature values.

The SFHs appear to be different between the fields. While both have $> 1\sigma$ detections of ancient stars, the central field shows significant star formation until 2 Gyr ago. Large amounts of recent (2 – 8 Gyr old) star formation are not ruled out in the outer field, though they appear to be $\sim 1/3$ the amount seen in the inner field. The mean metallicity (measured independently in the two fields) has increased from $[M/H] = -1.07 \pm 0.33$ 8 – 15 Gyr ago, to -0.42 ± 0.20 4 – 8 Gyr ago, to $[M/H] > -0.17$ 2 – 4 Gyr ago. These results (both the ages and metallicities) are consistent with ground-based studies (Layden & Sarajedini 1997; Marconi et al. 1998; and Bellazzini, Ferraro, & Buonanno 1999).

3. Conclusions

I have shown measurements of the SFHs of seven dwarf spheroidal companions. While each data set had a different quality (number of stars, photometric depth, and amount of foreground contamination), the ability to accurately determine uncertainties allows one to give the best answer and the uncertainty in the measurement for each object. Thus a SFH can always be measured – even with the very poor Sculptor CMD – but better data will naturally result in smaller uncertainties.

In every case, the calculated SFH agreed with what was qualitatively expected from a casual examination of the CMD. In all but one case, the distance and extinction (which were allowed to be free parameters) were determined correctly. It is worth noting that, even with imperfect isochrones, all eight CMDs were fit reasonably well. It is particularly encouraging that two independent measurements of the Sagittarius dwarf returned the same distance and same chemical enrichment history, despite having more foreground stars than Sagittarius stars.

Conclusions about star formation histories are limited by the fact that only a small fraction of each galaxy was studied. The Leo spheroidals had sufficient numbers of stars for accurate SFH measurements; the others produced only rough SFHs. The consistent feature of the SFHs is that ancient (> 8 Gyr) star formation was detected in all eight CMDs at the 1σ level. After the ancient burst, some (Ursa Minor, Draco, and Sculptor) show no evidence of young star formation. Leo II shows star formation covering about half its lifetime, while Carina and Sagittarius appear to have formed stars until ~ 2 Gyr ago. Leo I shows a very strong young burst, with its star formation rate $2 - 3$ Gyr ago nearly four times its lifetime average.

References

- Bellazzini, M., Ferraro, F.R., & Buonanno, R. 1999, MNRAS, 307, 619
 Carney, B. W. & Seitzer, P. 1986, AJ, 92, 23
 Carretta, E. et al. 2000, ApJ, 533, 215
 Da Costa, G. S. 1984, ApJ, 285, 483
 Dolphin, A. E. 2000a, PASP, 112, 1383
 Dolphin, A. E. 2000b, PASP, 112, 1397
 Dolphin, A. E. 2002, MNRAS submitted
 Dolphin, A. E. et al. 2001, ApJ, 550, 554
 Gallart, C. et al. 1999, AJ, 118, 2245
 Girardi, L. et al. 2000 A&AS, 141, 371
 Grillmair, C. J. et al. 1998, AJ, 115, 144
 Held, E. V. et al. 2000, ApJ, 530, L85
 Hernandez, X., Gilmore, G., & Valls-Gabaud, D., 2000 MNRAS, 317, 831
 Hurley-Keller, D., Mateo, M., & Nemec, J. 1998, AJ, 115, 1840
 Layden, A. & Sarajedini, A. 1997, ApJ, 486, L107
 Marconi, G. et al. 1998, A&A, 330, 453
 Mighell, K. J. 1997, AJ, 114, 1458
 Mighell, K. J. & Burke, C. J. 1999, AJ, 118, 366
 Mighell, K. J. & Rich, R. M. 1996, AJ, 111, 777
 Monkiewicz, J. et al. 1999, PASP, 111, 1392
 Olszewski, E. W. & Aaronson, M. 1985, AJ, 90, 2221
 Saha, P. 1998, AJ, 115, 1206
 Smecker-Hane, T. A. et al. 1994, AJ, 108, 507