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Reconstructing the Star Formation History of the Magellanic Clouds

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Abstract. We are developing an algorithm to determine the star formation history (SFH) of a mixed stellar population. We will apply the algorithm to hundreds of regions in our Magellanic Clouds Photometric Survey data and reconstruct the spatially resolved star formation history of the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC). In this paper, we demonstrate the algorithm on a typical region in the LMC, focussing on the obstacles and challenges facing us in attempting to reliably extract the SFH from photometric data.

1. Introduction

The evolution of a galaxy is defined by its star formation history (SFH): the star formation rate as a function of time, position and metallicity throughout the galaxy. Understanding the detailed SFH of resolved local group galaxies can potentially lead to a greater understanding of a variety of astrophysical problems, including the evolution of distant, unresolved galaxies, the propagation of star formation, and the role of galactic gravitational interactions. We are attempting to reconstruct the SFH of the Magellanic Clouds, using $UBVI$ photometry of their field stars. However, several challenges remain that must be resolved before the detailed SFH of these galaxies can be reliably extracted.

2. Data and Method

In Fig. 1, we present a $B-V, V$ color-magnitude diagram for approximately 57 000 stars in a randomly selected $24' \times 24'$ region of the LMC from our ongoing Magellanic Clouds Photometric Survey (for details, see Zaritsky et al. 1997). The survey will eventually provide $UBVI$ photometry for millions of stars in each of the Clouds.

We determine the SFH by identifying the best match between the observed photometric distribution and stellar evolutionary models. We use the Padua

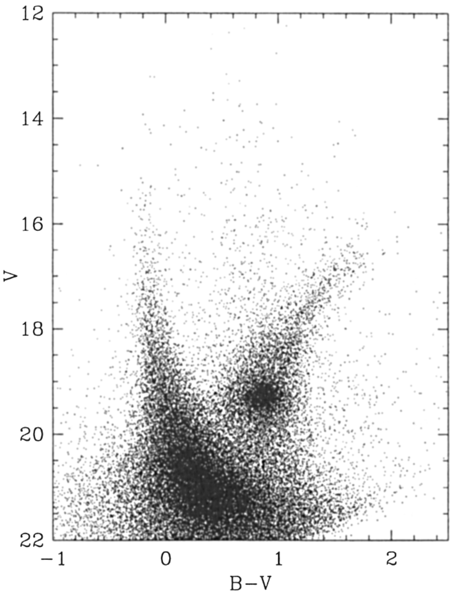

Figure 1. The $B-V, V$ color-magnitude diagram of the selected LMC region.

isochrones (Bertelli et al. 1994), due to their wide coverage in both age and metallicity. Each point along each isochrone is assigned a relative occupation probability (OP) based on a Salpeter IMF. The OP is distributed along the reddening line according to the observed reddening statistics (Harris et al. 1997) and error-blurred according to results from artificial star tests. These processes result in a library of model Hess diagrams. We then combine the model Hess diagrams linearly, assigning each an independent amplitude, to form a composite Hess diagram that can be compared to the data. The set of isochrone amplitudes describes the SFH of the model. To reduce the number of degrees of freedom in the model, we impose a chemical enrichment law. We will eventually allow metallicity choices at every epoch.

We use an "amoeba" algorithm to find the set of isochrone amplitudes that produces the best match to the observed Hess diagram. The algorithm starts at a randomly selected point in parameter space, and computes the likelihood of the resulting model. It then steps in each parameter dimension, and by recomputing the likelihood at these new locations, determines the local likelihood gradient. A step in the direction of the gradient is taken, and the procedure iterates until a maximum likelihood is found. To avoid local maxima, the amoeba takes a large step in each parameter dimension whenever a maximum is reached, to search for greater likelihood values. Finally, we restart the amoeba at another randomly selected position in parameter space, to see whether it returns to the same maximum. The derived SFH of the test region is shown in Fig. 2, a plot of the isochrone amplitudes of the most likely model.

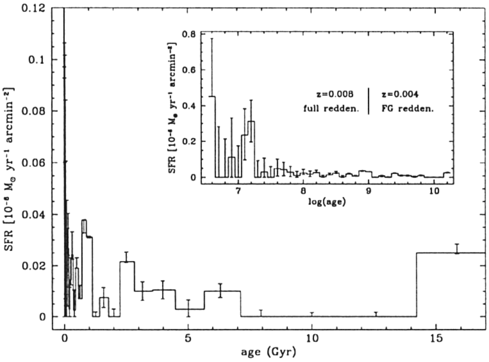

Figure 2. The derived SFH of the LMC region, normalized to $M_{\odot}\text{yr}^{-1}$.

3. Obstacles and Challenges

The derived SFH indicates an ancient burst of star formation, followed by 7 Gyr of quiescence, followed by an epoch of increasing, more or less continuous star formation activity that is continuing today. However, this is a work in progress, and we consider this result preliminary. There are observational, analytical and scientific issues that need to be understood and addressed before a reliable SFH can be presented.

3.1. Observational Issues

Some of the observational effects that need to be included in our analysis are: photometric errors and incompleteness, interstellar extinction, and foreground and background contaminants.

Statistical matching of observed photometry and models requires a highly detailed and accurate model of the observational uncertainties. Ideally, we would construct our error model by populating each image with artificial stars and repeating the photometric analysis. This would be done many times for each image, to build up statistics without significantly altering the crowding statistics of the frame. Such artificial star tests provide accurate measures of random and systematic errors, and photometric completeness as functions of photometric position, for the exact observing conditions and stellar density of each observed region. However, this procedure is computationally prohibitive. Instead, we use a library of artificial stars tests to develop fitting functions that relate observational errors to seeing, stellar surface density, sky brightness, nebulosity, and any other effects that vary from region to region in our data set. The validity of this parameterization of the errors will need to be firmly established.

Interstellar reddening must be accounted for in reconstructing an accurate SFH. We use the photometry of OB stars to determine the reddening as a function of position in the Clouds (see Harris et al. 1997). Isochrones can be statistically reddened according to these measurements, but the extrapolation of the reddening properties of OB stars to other stellar populations may be invalid, because OB stars may occupy particularly dusty regions of galaxies. To account for this bias, we use the foreground Galactic reddening maps of Oestreicher et al. (1995) for isochrones older than 1 Gyr. The narrow observed red giant branch and the color of the red clump indicate that older populations in the LMC do have lower reddening than our OB stars.

Finally, there is the issue of photometric contamination by objects outside the LMC. These are primarily main sequence stars in the Milky Way halo (which produce a vertical plume of stars in the CMD at $B-V \sim 0.6$) and background galaxies and quasars. For the most part, the galaxies and quasars are a small fraction of the objects in the CMD, and they occupy evolutionarily insensitive regions of the diagram, so they carry little weight in distinguishing between competing SFH models. However, the foreground stellar plume intersects the red supergiant and red giant branch regions, and could bias our results. We will account for the foreground plume either by including a simple foreground halo distribution of main sequence stars in our models, or preferably, by statistically subtracting foreground stars using similarly obtained and reduced control fields near the Magellanic Clouds.

3.2. Analytical Issues

The analytical issues that we need to resolve include: robustness of the fitting statistic, accurate estimates of the fit errors, and the determination of the chemical enrichment history.

There are indications that our maximum likelihood fitting statistic is not sufficiently robust. The fit penalizes models that predict few stars where many are observed more heavily than it penalizes models that predict many stars where few are observed. A fitting statistic that weights the lack of stars as heavily as their presence would be ideal. We are presently experimenting with a χ^2 fitting statistic as an alternative to the maximum likelihood fit. In this algorithm, we divide the CMD into regions, and compute the χ^2 values of each region's observed and predicted star counts. We then use the amoeba algorithm to find the model that minimizes the sum of the χ^2 values of each CMD region. Contrast this with the maximum likelihood method, which treats the model as a continuous occupation probability distribution, and sums the logarithm of the probabilities at the location of each observed star. The χ^2 method also provides a straightforward way to differently weight regions of the CMD. A potential problem with this method is that it has numerical difficulties if any region is either not observed or not predicted to be populated. We can overcome this problem by using an adaptive grid that is coarse where few stars are expected, and fine in densely populated regions.

Whatever our final choice of fitting statistic, the estimation of the fit errors is critical. We currently do not account for any correlation among the amplitude errors of different isochrones, which is incorrect because the integrated star formation rate is constrained by the total number of stars observed. One isochronal amplitude cannot be adjusted without incurring a change in another. Therefore, the confidence intervals in Fig. 2 underestimate the true fit errors.

Finally, we have imposed a chemical enrichment law by only providing one metallicity option at each age in our isochrone basis set. We chose the metallicities based on what is known for LMC populations, but it would be better to provide isochrones with a range of metallicities at each age, and allow the algorithm to determine the best combination. The latter provides the potential for uncovering not only the chemical enrichment history, but the range of metallicities present at each epoch. However, determining the chemical enrichment history in detail using photometry may be impossible, because photometry is relatively insensitive to metallicity effects. Furthermore, systematic errors in the isochrones may render our current attempt to measure chemical enrichment futile (see below).

3.3. Scientific Issues

Using theoretical models to interpret data assumes that the theory encapsulates reality. There are several areas in our modeling where this assumption can be questioned, including the stellar binary fraction, the nature of the initial mass function (IMF), and systematics of the stellar models. In addition, determination of spatial variations in the SFH are limited by the random motions of the stars.

We currently do not account for binary stars in our photometric models, which could significantly bias our results, if the binary fraction is large in the Magellanic Clouds. However, our ground-based data do not contain stars less massive than about $M = 1.5 M_{\odot}$. If the stellar masses in binary pairs are uncorrelated, most binaries in our sample will be insignificantly altered by their less massive companion. We will simulate binary stars (both with and without correlated stellar masses) in artificial photometric distributions to determine their effect.

Our photometric models draw stellar masses randomly from a Salpeter IMF. If the distribution of stellar masses in the Magellanic Clouds differs from Salpeter, we will converge upon the wrong SFH. Recent work indicates some cause for concern. Massey et al. (1995) found that while massive stars in OB associations are absolutely consistent with the Salpeter IMF, OB stars that appear to have formed in low stellar density environments show a much steeper logarithmic IMF slope. In addition, Parker et al. (1998) found that the most probable IMF slope for LMC stars is $\Gamma = -1.8$, significantly steeper than the Salpeter value ($\Gamma = -1.35$).

A larger potential problem lies in the isochrones themselves. If there are systematic errors in the photometric location of CMD features, then we will converge on the wrong SFH. Some indications in the literature exist that the isochrones may indeed have problems in some regions (Buonnano et al. 1998, Richtler et al. 1998). We are attempting to investigate possible isochrone systematics by examining published CMDs of star clusters, which represent a population of stars with a single metallicity and age. If the clusters' CMD features are well-traced by the corresponding isochrone, we can proceed with increased confidence. If there are differences, perhaps we can perform empirical photometric corrections to the isochrones, use the cluster fiducials themselves as our basis set, or avoid uncertain regions of the CMD.

As a final note, we need to be aware that random stellar motions will limit the precision with which we can spatially resolve the SFH. Stellar populations become mixed over time, and it becomes increasingly difficult to associate stellar populations with localized star formation events.

4. Conclusions

The Magellanic Clouds Photometric Survey is providing a wealth of data and a promising opportunity to determine the star formation history of the Magellanic Clouds in great detail. However, the reliable extraction of the SFH from multicolor stellar photometry is not trivial. There are a number of complicating issues that need to be resolved in constructing a model to compare to these data. The models must include an accurate photometric error and completeness model, and the effects of interstellar extinction. In addition, the fitting statistic needs to be robust against the presence of foreground and background contaminants and non-Gaussian errors, but sensitive enough to extract details from the CMD. Finally, there are scientific uncertainties, including the IMF slope, the binary fraction, the chemical enrichment history, possible systematic errors in the isochrones, and the dynamical evolution of the stellar populations. Each of these issues can lead our algorithm to converge on the incorrect SFH.

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Discussion

Aparicio: (1) You obtain SFR $\simeq 0$ for age 7 to 14 Gyr - why? What feature of the CMD is associated with the lacking of stars in that time interval? (2) What chemical enrichment law are you using? (3) How sure are you about the time resolution you have shown for the young ages?

Zaritsky: (1) There are three time bins with zero star formation, although the plotted uncertainties allow for some star formation. Because of the preliminary nature of the analysis I would not be surprised to find a more moderate star formation rate in our later analysis. (2) We have taken a two step approach (with the older population, log(age) > 9, at $z = 0.004$, and the younger at $z = 0.008$). Eventually we want to attempt to solve for the SFH and chemical enrichment simultaneously. (3) We have taken $\Delta(\log t) = \text{const}$, which leads to small age resolution at young ages. We are still investigating the robustness of fits to various parameter choices.

Terndrup: Your diagram of the SFR as a function of time qualitatively looks like the LMC cluster age distribution. Would you like to comment on the similarities or differences between the two?

Zaritsky: Qualitatively they are indeed very similar, with an old population, a gap, and an increase in the star formation rate in the last few Gyr. Our results are too preliminary for us to make quantitative conclusions at this point.