Guy Worthey
Major Papers with Abstracts

Hubble Space Telescope Observations of M32: The Color-Magnitude Diagram

Carl J. Grillmair et al.
1996 AJ, 112, 1975

We present a VI color-magnitude diagram for a region $1' - 2'$ south of the center of M32 based on *Hubble Space Telescope* WFPC2 images. The broad color-luminosity distribution of red giants shows that the stellar population comprises stars with a wide range in metallicity. This distribution cannot be explained by a spread in age. The blue side of the giant branch rises to $M_I \approx -4.0$ and can be fitted with isochrones having [Fe/H] ≈ -1.5. The red side consists of a heavily populated and dominant sequence that tops out at $M_I \approx -3.2$, and extends beyond $V - I = 4$. This sequence can be fitted with isochrones with $-0.2 <$ [Fe/H] $< +0.1$, for ages running from 15 Gyr to 5 Gyr respectively. We do not find the *optically* bright asymptotic giant branch stars seen in previous ground-based work and argue that the majority of them were artifacts of crowding. Our results are consistent with the presence of the *infrared*-luminous giants found in ground-based studies, though their existence cannot be directly confirmed by our data. The tip of the metal-poor portion of the giant branch occurs at the luminosity expected if M32 is at the same distance as M31 but is too sparsely sampled by this data set to provide a precise distance estimate. At fainter magnitudes, the rising giant branch is significantly wider ($\mathrm{FWHM}_{V-I} \sim 0.6$ mag down to $M_I \sim -1.0$) than can be accounted for by photometric uncertainties, again due to a metallicity spread. There is little evidence for an extended or even red horizontal branch, but we find a strong clump on the giant branch itself, as expected for the high metallicities inferred from the giant branch. If the age spread is not extreme, the distribution of metallicities in M32 is considerably narrower than that of the closed-box model of chemical evolution, and also appears somewhat narrower than that of the solar neighborhood. Overall, the M32 *HST* color-magnitude diagram is consistent with the average luminosity-weighted age of 8.5 Gyr and [Fe/H]≈ -0.25 inferred from integrated spectral indices, extrapolated to this radius and analyzed with the same population models.

The G Dwarf Problem Exists in Other Galaxies

Guy Worthey, Ben Dorman, and Lewis A. Jones

1996 AJ, 112, 948

Stellar population models with abundance distributions determined from the analytic Simple model of chemical evolution fail to match observations of the nuclei of bulge-dominated galaxies in three respects. First, the spectral energy distribution in the mid-ultraviolet range $2000 < \lambda < 2400$ Å exceeds observation by ~ 0.6 mag. Most of that excess is due to metal-poor main sequence stars. Second, the models do not reproduce metal-sensitive optical absorption features that arise mainly from red giant stars. Third, the strength of a Ca II index sensitive to hot stars does not jibe with the predicted number of A-type horizontal branch stars. The number of metal poor stars in galaxies is at least a factor of two less than predicted by the Simple model, exactly similar to the "G Dwarf problem" in the solar cylinder. Observations at larger radii in local group galaxies indicate that the paucity of metal poor stars applies globally, rather than only in the nuclei.

Because of the dominance of metal rich stars, primordial galaxies will have a plentiful dust supply early in their star formation history, and thus will probably have weak Lyα emission, as is apparently observed. We confirm that early-type galaxies cannot have been formed exclusively from mergers of small all-stellar subsystems, a result already established by dynamical simulations. The constraint of peaked abundance distributions will limit future chemical evolution models. It will also make age estimates for the stellar populations in early type galaxies and bulges more secure.

Uncertainties in the Modeling of Old Stellar Populations

Stéphane Charlot, Guy Worthey, and Alessandro Bressan

1996 ApJ, 457, 625

We compare three recent models for the spectral evolution of stellar populations to assess the origin of serious discrepancies in the colors predicted for $\gtrsim 1$ Gyr old populations of the same input age and metallicity. To isolate the source of these discrepancies, we investigate separately the two main characteristics of each model: the underlying stellar evolution prescription and the spectral calibrations used to transform the theoretical Hertzsprung-Russell diagram into observables. A 0.05 mag discrepancy in $B - V$ color is caused almost entirely by a known limitation of theoretical spectra. Differences in spectral calibrations are found to account for only a small fraction of the 0.25 mag discrepancies in $V - K$ color and of the 25% dispersion in mass-to-visual light ratio among the models considered here. The main source of disagreement for these quantities is the underlying stellar evolution prescription.

For idealized galaxies containing a single generation of stars, properties derived from broad-band colors using population synthesis models are found to be accurate by roughly ±35% in age at fixed metallicity, 25% in metallicity at fixed age if the heavy element mixture is assumed to be scaled-solar, and 35% in mass at fixed metallicity and fixed initial mass function. These indicative uncertainties are based on the dispersion in the predictions of the models investigated here.

There appear to be persistent problems in virtually every ingredient of population synthesis models. The most serious are the lifetimes and luminosities of stars in post-main sequence evolutionary stages; the temperature of the red giant branch and color-temperature relation for cool stars; and the lack of accurate libraries of stellar spectra, especially for cool stars and for non-solar metallicities. These problems have profound causes. The main one is the high sensitivity of stellar evolution models on the efficiency of several critical factors which are either not sufficiently understood or cannot yet be determined uniquely from comparisons with observations (opacities, heavy element mixture, helium content, convection, diffusion, mass loss, rotational mixing). Other major limitations are the difficult spectral modeling of cool stars and the unavailability of calibration stars for metal-rich populations and populations with altered chemical mixes.

New Age Indicators for Old Stellar Populations

Lewis A. Jones and Guy Worthey

1995 ApJ (Letters), 446, L31

We report on new age indicators in the integrated light of old stellar populations. Spectral indices defined by Rose in the $\lambda\lambda$ 3800–4500 Å region and two broader indices, Hδ_A and Hγ_A, have been measured in a spectral library of about 500 stars. The behavior of these indices with temperature, gravity, and [Fe/H] was modeled with polynomials, and they were included in the population models of Worthey (1994). All definitions of Hδ and Hγ are sensitive to population age. One index in particular, Hγ_{HR}, shows a striking ability to separate the effects of age and metal abundance in integrated light.

Comprehensive Stellar Population Models and the Disentanglement of Age and Metallicity Effects

1994 ApJS, 95, 107

The construction of detailed models for intermediate and old stellar populations is described. Input parameters include metallicity ($-2 <$ [Fe/H] < 0.5), single-burst age (between 1.5 and 17 Gyr), and IMF exponent. Quantities output include broad-band magnitudes, spectral energy distributions, surface brightness fluctuation magnitudes, and a suite of 21 absorption feature indices. The models are checked against a wide variety of available observations. Examinations of model output yield the following conclusions. (1) If the percentage change $\Delta\mathrm{age}/\Delta Z \approx 3/2$ for two populations, they will appear almost identical in most indices. A few indices break this degeneracy by being either more abundance-sensitive (Fe4668, Fe5015, Fe5709, Fe5782) or more age-sensitive (G4300, Hβ, and presumably higher-order Balmer lines) than usual. (2) Present uncertainties in stellar evolution are of the same magnitude as the effects of IMF and Y in the indices studied. (3) Changes in abundance ratios (like [Mg/Fe]) are predicted to be readily apparent in the spectra of old stellar populations. (4) The I band flux of a stellar population is predicted to be nearly independent of metallicity, and only modestly sensitive to age. The I band is therefore recommended for standard candle work or studies of M/L in galaxies.

Other conclusions stem from this work. (1) Intercomparison of models and observations of two TiO indices seem to indicate variation of the [V/Ti] ratio among galaxies, but it is not clear how this observation ties into the standard picture of chemical enrichment. (2) Current estimates of [Fe/H] for the most metal-rich globulars that are based on integrated indices are probably slightly too high. (3) Colors of population models from different authors exhibit a substantial range. At solar metallicity and 13 Gyr, this range corresponds to an age error of roughly ± 7 Gyr. Model colors from different authors applied in a differential sense have smaller uncertainties. (4) In the present models the dominant error for colors is probably the transformation from stellar atmospheric parameters to stellar colors. (5) Stellar $B-V$ is difficult to model, and current spreads among different authors can reach 0.2 mag. (6) If known defects in the stellar flux library are corrected, the population model colors of this work in passbands redder than U would be accurate to roughly 0.03 mag in an absolute sense. These corrections are not made in the tables of model output.

Old Stellar Populations V.
Absorption Feature Indices for the Complete Lick/IDS Sample of Stars

Guy Worthey, S.M. Faber, J. Jesús González, D. Burstein

1994 ApJS, 94, 687

Twenty-one optical absorption features, 11 of which have been previously defined, are automatically measured in a sample of 460 stars. Following Gorgas et al., the indices are summarized in fitting functions that give index strengths as functions of stellar temperature, gravity, and [Fe/H]. This project was carried out with the purpose of predicting index strengths in the integrated light of stellar populations of different ages and metallicities, but the data should be valuable for stellar studies in the Galaxy as well. Several of the new indices appear to be promising indicators of metallicity for old stellar populations. A complete list of index data and atmospheric parameters is available in computer-readable form.

A Method for Quantitative Detection of Hot Horizontal Branches in Early-type Galaxies

1993 ApJ (Letters) 415, L91

Surface brightness fluctuation magnitudes in the λ2800–4000Å region are calculated. They show that a hot main sequence can be easily distinguished from a hot horizontal branch due the relative sensitivity of fluctuation magnitudes to the presence of giants. Superluminous post-asymptotic giant branch (PAGB) stars will need to be subtracted before applying this method, and other hypothesised late-stage, hot stars may also contribute to the surface brightness fluctuation magnitudes, complicating the analysis. Application of this method further in the UV will provide an estimate of the luminosity of the next-most-luminous subpopulation of stars after the PAGB stars, which will constrain the possible populations responsible for the UV flux in ellipticals.

The Dependence of the Brightness Fluctuation Distance Indicator on Stellar Population Age and Metallicity

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Erratum 1993 ApJ, 418, 947

We describe how the extragalactic distance indicator $\overline{L}$ depends on stellar population age, metallicity, and IMF, assuming single-burst ages between 5 and 17 Gyr and metallicities between –0.5 and +0.5 dex. We consider Johnson/Cousins $BVR_CI_CJHKLL'M$ passbands. We find that (1) $\overline{L}$ is insensitive to changes in IMF, (2) $\overline{L}$ can be reliably calibrated against colors or spectral indices, due to the similarity of the effects of age and metallicity on the stellar populations, (3) the calibration presented here may already give distances good to 10% for an isolated galaxy measured in one fluctuation passband and one color or spectral index, not including observational error, and (4) our theoretical results are consistent with the distance of M32 and with the latest empirical $\overline{I}$ calibration and require no empirical corrections. We summarize our results by giving polynomial calibrations for $\overline{M}$ as functions of integrated Mg_2, V–I, and J–K.

Mg and Fe Absorption Features in Elliptical Galaxies

Guy Worthey, S.M. Faber, & J. Jesús González

1992 ApJ, 398, 69

Fe and Mg indices from two homogenous collections of nuclear elliptical galaxy spectra are compared with model indices. In the average giant elliptical, the [Mg/Fe] ratio exceeds that of the most metal-rich stars in the solar neighborhood by $\sim 0.2 - 0.3$ dex, with a large spread about this mean. This result implies a variable "enrichment effectiveness" of Type II supernovae (SNe) compared with Type Ia SNe in the evolution of ellipticals, caused perhaps by differences in star formation timescales, the initial mass function, or the amount of Fe vs. Mg ejected in galactic winds.