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STELLAR POPULATIONS IN GALAXIES: PROGRESS ON THE MILKY WAY, ON DWARF IRREGULARS, AND ON ELLIPTICAL GALAXIES

Dante Minniti[1]

Depto. de Astronomía, Pontifícia Universidad Católica, Santiago, Chile;
and IGPP, Lawrence Livermore Natl. Lab., U.S.A.

RESUMEN

Gran progreso está ocurriendo en el campo de poblaciones estelares. Surveys como el Proyecto MACHO contribuyen al conocimiento de la estructura interna de nuestra galaxia. Los diferentes componentes (bulbo, halo, disco delgado y grueso) se entremezclan hacia las regiones interiores galácticas. Podemos aprender mucho sobre estas poblaciones usando la base de datos del Proyecto MACHO. Otra gran base de datos, el SDSS, también contribuirá al conocimiento de las partes mas distantes del halo galáctico. Estrellas de rama horizontal azules serán identificadas con este propósito. Se discuten observaciones recientes de galaxias enanas irregulares, para determinar su contenido estelar y cómo se formaron. Además, ahora es posible obtener diagramas color-magnitud de galaxias lejanas, fuera del Grupo Local. Se describen observaciones recientes de la galaxia temprana gigante NGC 5128.

ABSTRACT

I discuss specific topics of stellar populations where major progress is occurring. Large surveys like the MACHO Project are contributing to our understanding of the inner structure of our Galaxy. Towards these inner regions, different components (bulge, inner halo, and inner thin and thick disks) overlap. We can learn much about these stellar populations using the MACHO database. We expect major progress in the study of the outer Milky Way halo in following years from the SDSS database. Very distant BHB stars located in the outskirts of the halo would be identified. I also describe recent observations of nearby dwarf irregular galaxies, and discuss what they tell us about their stellar content, and about the way these galaxies form. It is now possible to construct deep luminosity functions and color-magnitude diagrams for galaxies beyond the Local Group. I finally review recent work on the resolved stellar populations of the giant early type galaxy NGC 5128.

Key Words: **GALAXIES: NGC 3109, WLM, NGC 5128 — GALAXIES: SPIRALS, DWARF IRREGULARS, GIANT ELLIPTICALS — MILKY WAY: HALO, DISK — STARS: RR LYRAE, BHB — STARS: STELLAR POPULATIONS**

1. INTRODUCTION

A modern definition of Population II stars can be old (age> 10^{10} yr), metal-poor ($[Fe/H] < -1$), and kinematically hot (low rotation and high velocity dispersion). A modern definition of Population I stars can be young, metal-rich, and kinematically cold stars (with high rotation and low velocity dispersion). However, the concepts of stellar populations have changed since Baade (1944): it is no longer very useful to speak of Population I or II stars (Olszewski et al. 1996a, 1996b), now that we know much more about the physical parameters of stars, about stellar dynamics, and about the star formation histories of galaxies. So the Population

[1]dante@astro.puc.cl

I and II concepts should be abandoned, because they can now lead to contradictions or confusion. For example, Galactic bulge stars are old and metal-rich, and do not fit these traditional definitions. With the advent of large telescopes and efficient detectors, it is now possible to resolve distant galaxies into stars. This also gets us into trouble with the traditional definitions of Populations, because we can now measure directly individual stellar properties, and can find examples of old and metal-rich populations that are kinematically hot (e.g., NGC 5128), or young and metal-poor populations that are kinematically cold (e.g., WLM and NGC 3109).

The good news is that classical extragalactic astronomy has been transformed in stellar astronomy: it is no longer necessary to rely on the integrated photometric or spectroscopic properties of nearby galaxies, we can now directly observe their constituent stars. This determines that the predictions of population synthesis based on the integrated light of star clusters (e.g., Bica 1988) and galaxies (e.g., Bruzual & Charlot 1993; Gonzalez & Gorgas 1995) can now be tested directly for nearby galaxies (nearby means $d < 10$ Mpc) The work of extragalactic population synthesis is now being applied to more distant systems, at intermediate and high redshifts (Pello et al. 1998), but it is anchored on the detailed knowledge that we acquire by resolving local galaxies into stars. Here I discuss a few specific cases of stellar populations in galaxies where great progress has been achieved or is going to occur.

2. PROGRESS ON THE MILKY WAY: LARGE DATABASES

Major scientific advances on the Milky Way are currently due to large surveys. In the future, these surveys are going to drive more and more local stellar population studies. I discuss two specific surveys: the MACHO (MAssive Compact Halo Objects) Project database, which is currently the largest astronomical database, and the SDSS (Sloan Digital Sky Survey), which *circa* 2005 will become the largest existing database. The large areas and timescales covered by these and other large databases are illustrated in Figure 1.

2.1. *The MACHO Project Database: The Future Is Here*

The MACHO microlensing experiment has a dedicated telescope that has imaged fixed sky fields night after night for several years in two passbands (Figure 1). These observations now form a database with >5 TeraB, which is ideal for the study of stellar populations, variable stars and Galactic structure.

The MACHO nightly photometry is done in two bands (roughly V and R), containing now more than 4×10^7 stars in the bulge, in the LMC, and in the SMC (see **http://wwwmacho.mcmaster.ca**). As byproducts of these observations, many ($N > 10^5$) variable stars of different kinds have been discovered in a few seasons. These variable stars are particularly important as they trace different stellar population components in the Milky Way, allowing the study of the sizes and shapes of the bulge, disk and halo.

Some of the most interesting variable stars are RR Lyrae, which not only trace the oldest Milky Way populations ($age > 10^{10}$ yr), but also are excellent distance indicators. RR Lyrae are found the extent of the Milky Way halo. MACHO found $N = 1400$ RRab and RRc in the bulge fields (Minniti et al. 1997). These tracers define the density law and total luminosity of the halo and inner Milky Way bulge (Alcock et al. 1998).

Large numbers of eclipsing binaries with periods of 0.25d to > 1000d are found ($N = 10^4$ in the disk, halo and bulge). For the first time, accurate binary fractions and period distributions can be measured for different Galactic populations. Spectroscopic follow up of selected systems can give accurate masses and distances. From these one can infer the line of sight distribution and scale-length of the disk (e.g., Rucinsky 1996).

Long period pulsating stars are also important to study the structure of the Milky Way. In particular, LPVs, semiregulars and Mira variables are numerous in the inner regions of the Galaxy. Thanks to the improved P-L relations for these kinds of variables given by *Hipparcos* (Bedding & Zijlstra 1998), it would be possible to measure distances and the 3-D structure of the inner bulge and halo (e.g., Minniti et al. 1998a).

Note that even with only one measurement per day, accurate periods down to 0.05–0.08 days can be achieved without aliasing given a 3–5 years coverage, because the sampling of the phase is random. This allows the discovery and study of single and multi-mode δ Sct stars, which are among the most numerous variables known. Understanding their pulsation gives an important handle on the internal structure of stars. Interestingly, the δ Sct stars are good bulge tracers, and would allow an independent measurement of R_0 (the distance to the Galactic center), if their period-luminosity relations can be improved (e.g., Minniti et al. 1998b).

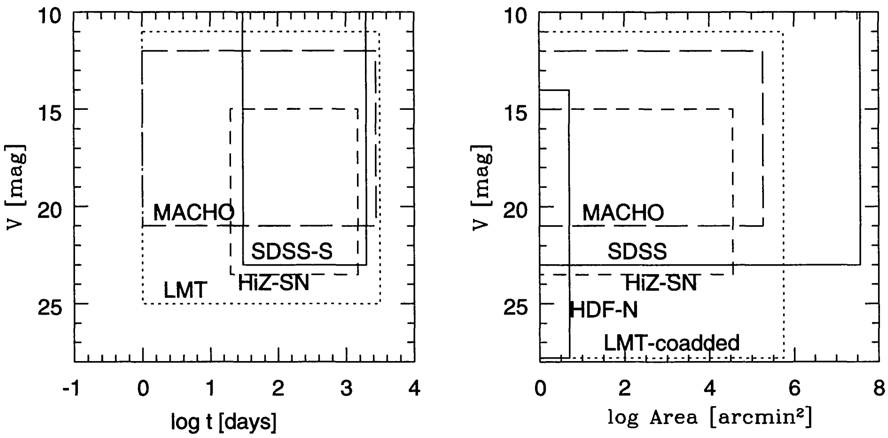

Fig. 1. Left panel: Magnitude *vs* temporal coverage of large surveys: MACHO, SDSS-South, HiZ-SN search, and the future LMT (Liquid Mirror Telescope) in Chile. Right panel: Magnitude *vs* total area covered by the large surveys. For comparison, we have added the areal coverage of the whole SDSS, the Hubble Deep Field North and the coadded LMT survey.

Clump giants are present in metal-rich populations, and can be excellent tracers of the bar in the inner Milky Way. They can be used as distance indicators, having been recently calibrated by *Hipparcos*. Counts of these clump giants will allow a precise measurement of the scale-height of the metal-rich bulge population.

The understanding of these variable stars locally would be an advantage for the interpretation of similar populations discovered in nearby galaxies (e.g., with the *HST*). Databases like that of MACHO also allow the study of nearby galaxies, like the Sgr dwarf, located behind the Galactic bulge. Variable stars are numerous in the Sgr dwarf: the Sgr RR Lyrae, Miras and Long Period variables would give information on the stellar content of this galaxy. They also allow for the first time the study of the 3D structure (extension in the sky and depth along the line of sight), and total luminosity of a MW satellite (e.g., Alcock et al. 1997a). This provides a direct account of the process of tidal disruption of a satellite that is being accreted by a larger galaxy (e.g., Mateo et al. 1998; Velázquez 2001).

2.2. *The Sloan Digital Sky Survey: What's Coming*

The Sloan Digital Sky Survey is an ambitious extragalactic undertaking, aimed at thousands of quasars and millions of distant galaxies, that will contain up to 10 TeraB of data when completed. As byproducts of this survey photometry of $N = 10^8$ and spectroscopy of $N = 10^5$ foreground stars in our Galaxy will be obtained. All these data will be made public (Gunn et al. 1998; Margon 1998).

Even though the variability information of the SDSS is more limited than the MACHO Project (only the Southern strip SDSS-S has multiple epochs), the SDSS will contribute in a similar way to studies of stellar populations and Galactic structure. Among the non-variable stars, it would be possible to search for stellar tracers of high latitude streams and "spaghettis" resulting from past accretion events in the history of the Milky Way (e.g., Alcock et al. 1997b). Tracers like high latitude BHB stars, RR Lyrae stars, white dwarfs, and C-type stars would be easily found using color-color diagrams. This is illustrated in Figure 2, which shows a simulated halo field observed with SDSS (from Fan 1999). There are $N = 26,000$ stars in this simulation, mostly located in a tight sequence in color-color diagrams. Note the expected contribution from large number of nearby late type dwarfs with $r' - i' > 1.0$. Other extragalactic sources like QSOs and compact emission line galaxies can be discriminated using additional colors (Fan 1999; Krisciunas et al. 1999).

What could we learn from the SDSS stars? Something specific that we could know is the extent and structure of the outer Milky Way halo using RR Lyrae and BHB stars. Existing samples map the halo out to only the distance of the LMC $d < 50$ kpc (e.g., Layden 1998), and the more distant halo is not known. But

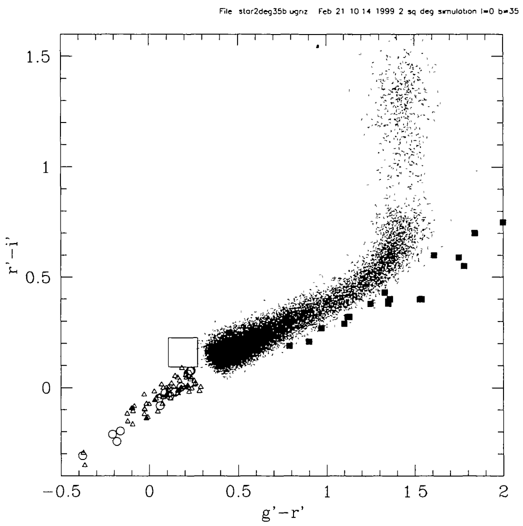

Fig. 2. Simulated $g' - r'$ *vs* $i' - r'$ color-color diagram for a 2 sq deg halo field at $l,\ b = (0°,\ 35°)$. This figure shows how interesting objects can be selected: points are normal stars, full squares are carbon stars, open triangles are BHB stars, open circles are white dwarfs, and the big open square is the location of RR Lyr stars with mean $[Fe/H] = -1.6$. The simulated stellar data is taken from Fan (1999), and the carbon stars and RR Lyr sequence are taken from Krisciunas et al. (1999).

we know from kinematics of Milky Way satellites that the dark halo extends to distances in excess of 100 kpc. Finding tracers so far away has not been possible, the numbers of globular clusters for example diminishes quickly after 50 kpc. Note that the halo regions at $d > 50$ kpc would have an equivalent surface brightness beyond the surface brightness levels that can be observed in other galaxies.

BHBs are good distance indicators, and easy to detect due to their high luminosity and blue colors. *Hipparcos* results show that halo BHB should have $M_V = +0.65$ (de Boer 1999) for a mean halo metallicity $[Fe/H] = -1.6$ (Wheeler, Sneden & Truran 1989). High latitude RR Lyrae and BHB stars are very rare: their density is about 1 per sq deg. Now using the large SDSS database, many RR Lyrae and BHB stars can be found out to large distances (> 200 kpc), probing the outskirts of the Milky Way halo to unveal its formation process.

The BHB stars found in the outer halo by SDSS will help to solve some outstanding problems. For example, the distribution of halo tracers either 1) flattens towards the inner regions, or 2) contains two separate components (Preston et al. 1991). Also, the kinematics reveal that the halo stars in the direction of the NGP appear to be counterotating, while those at the SGP do not (Sommer-Larsen 1999). Different models predict radial or tangential anisotropy in the outer halo. In addition, UV spectroscopy of these stars would be useful (see Chávez 2001). Note also the important rôle that neural networks applied to large databases will have (Gulati et al. 2000). Finally, major advances in stellar populations would occur with the ESA proposed mission GAIA, as discussed by Brown (2001).

3. PROGRESS ON DWARF IRREGULAR GALAXIES

The current knowledge of star formation histories of galaxies along the Hubble sequence is summarized by Kennicutt (1998). The best known galaxies are the nearest ones, contained within the Local Group. In the Local Group we can see down to the end of the galaxy luminosity function, and in recent years a few more faint members have been added (Mateo 1998; Grebel 1999). Using the Local Group as a zero point is very important for understanding the more distant Universe.

Dwarf galaxies are the most numerous galaxies in the Local Group, and in the Universe as a whole (Mateo 1998). There are two types of dwarf galaxies: gas-poor dwarf spheroidals (dSph), and gas-rich irregulars (dIrr)

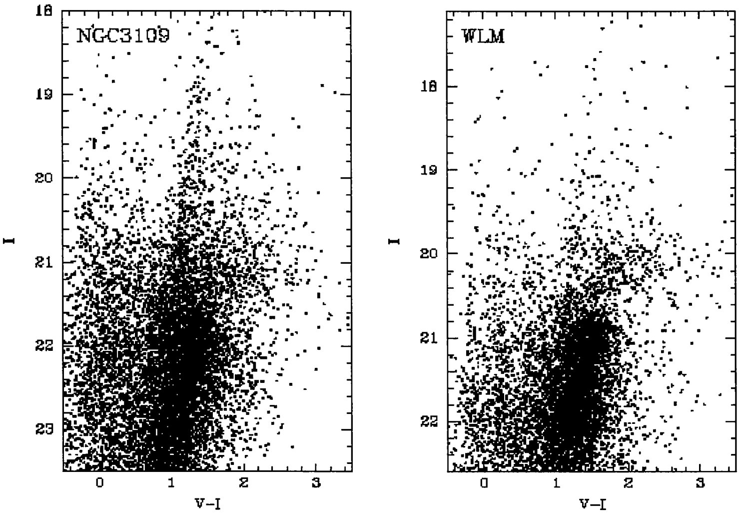

Fig. 3. Color-magnitude diagrams of the central regions (disk) of the dwarf irregulars NGC 3109 and WLM.

(see Mateo 1998 for a review). The dSphs are found primarily in the cores of clusters, indicating they have already undergone significant evolution through interaction (e.g., Bingelli, Tamman, & Sandage 1987). In the Local Group they are almost exclusively located close to the massive spirals (e.g., van den Bergh 1994). They have high M/L (up to 100) based on stellar velocity dispersions (Aaronson 1983; Olszewski et al. 1996a). The dIrrs, generally located far from massive spirals, are also believed to have dark matter halos, based on rising H I rotation curves. In general, their total M/L values are larger than those of normal spiral galaxies (e.g., Carignan & Freeman 1988; Navarro, Frenk, & White 1997).

Recent simulations of star formation histories of nearby galaxies allow us to take the leap to early times (Tolstoy 1999), to predict what nearby galaxies looked like in the past, and to compare with galaxy fields observed at cosmological distances. Below we discuss two specific cases.

3.1. *Resolving Distant Dwarf Galaxies Into Stars: WLM and NGC 3109*

NGC 3109 and WLM are dwarf irregular galaxies located at $D = 0.9$ Mpc and $D = 1.3$ Mpc, respectively. Lying far away from the dominant massive spirals, WLM and NGC 3109 are considered to be members of the Local Group (van den Bergh 1994). From least action principle considerations (Peebles 1995), it is likely that these galaxies have remained in a low density environment, at the edge of the Local Group. Figure 3 shows the color-magnitude diagrams of the disks of these galaxies. Multiple populations are present, with a wide range of ages going from very young ($t < 10^7$ yr) to very old ($t > 10^{10}$ yr). These diagrams are complicated by reddening and crowding, but can be simulated using theoretical isochrones in order to infer star formation histories (e.g., Aparicio 1998).

However, the color-magnitude diagrams of these disks do not tell the whole story. Aside from multiple populations, these galaxies have resolved structures. In particular, these normal looking dwarf irregulars have halos. Minniti & Zijlstra (1996) found an extended component of old and metal-poor stars around the Im IV–V galaxy WLM (DDO 221), the first such discovery in a dIrr galaxy. A similar halo was then discovered in NGC 3109 (Minniti et al. 1999a). Figure 4 illustrates how the color-magnitude diagram changes in the halos of these galaxies, away from the disk. These halos are old ($t > 10^{10}$ yr) and metal-poor ($[Fe/H] < -1$), as revealed by the location and extent of the red giant branch. Unfortunately, deep IR color-magnitude diagrams of dwarf irregulars are lacking (Alonso et al. 1999). The properties of the extended stellar component of these galaxies resemble the halos of other larger galaxies. For example, the properties of the Milky Way stellar halo are: 1) extended, 2) old, 3) metal-poor, 4) no gradients, and 5) kinematically hot. The WLM and NGC 3109

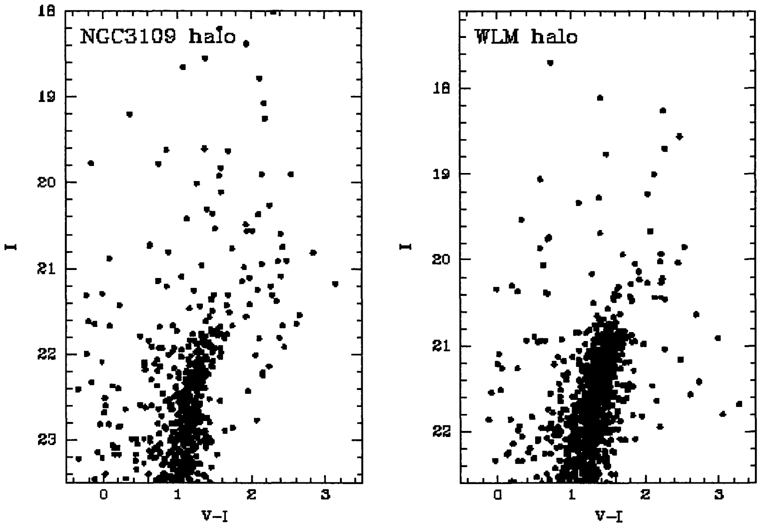

Fig. 4. Color-magnitude diagrams of the halos of the dwarf irregulars NGC 3109 and WLM. The scale is the same as Figure 3. Note that only old and metal-poor stars are present here.

halos fulfill these properties, except that their kinematics are not known because the stars lie beyond reach of 4m class telescopes. This can now be attacked observationally with 8m telescopes. If, as expected, the old stars form a spheroidal halo, it will be possible for the first time to measure the dark matter content from the halo velocity dispersion in an irregular galaxy, which can be compared to the H I measurement in the disk.

The importance of galactic halos in terms of galaxy formation theories was recognized very early on (Eggen et al. 1962), because they are the oldest measurable tracers from primordial times. The finding of a halo in dwarf irregular galaxies argues for a generic mode of galaxy formation that requires a halo in the presence of a disk, regardless of galaxy size. This implies that formation mechanisms are similar along the spiral Hubble sequence, regardless of disk type or luminosity. Halo formation also appears not necessarily to be related to the presence of a bulge or a nucleus, since WLM and NGC 3109 lack both of these components.

4. PROGRESS ON ELLIPTICAL GALAXIES

Giant ellipticals are luminous galaxies that can be seen to large distances. However, their formation remains uncertain. If they formed by mergers or accretion processes, the observed light would come from both old and intermediate age stars. If, on the other hand, they formed rapidly consuming all the gas, we should only see coeval stars. It has been difficult to decide among different scenarios, because the studies of their stellar populations have been based on photometry and spectroscopy in integrated light. Thanks to improvements in telescope sizes, sensitivity, and spatial resolution, we can now make luminosity functions and color-magnitude diagrams for the stars in more distant ellipticals and bulges. These allow to measure their distances, abundances and ages, and to compare with predictions from stellar evolutionary theory. The theory is well understood, having been tested and calibrated on star clusters spanning a wide range of ages and metallicities (e.g., Bica 1988). This method would complement the existing integrated spectroscopic data and would allow to study the stellar distribution, to separate the different populations, and to test scenarios of formation.

For example, *HST*+STIS and ACS will be able to reach the horizontal branches of all galaxies within the Local Group (Gregg & Minniti 1997). However, we still do not sample the whole Hubble sequence, because the Local Group lacks early type galaxies (aside from M32, which is peculiar in many respects). Based on integrated properties, stars in ellipticals appear to be predominantly metal-rich. As we know from studies of the Milky Way bulge, optical observations are not well suited for the study of metal-rich populations, because the optical colors saturate, becoming degenerate for $[Fe/H] > 0$ (Bica et al. 1991). It is still worth trying

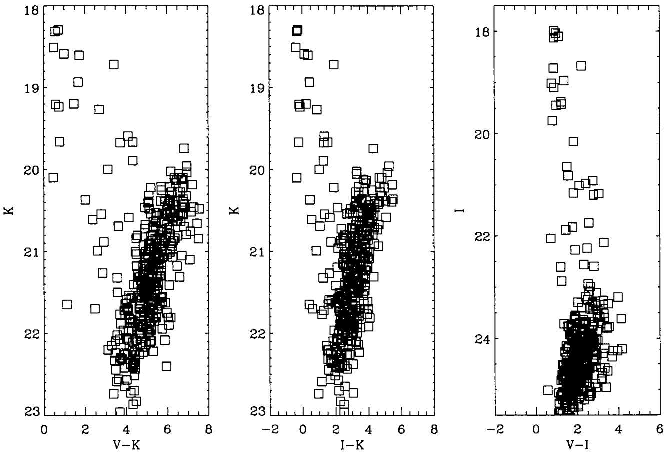

Fig. 5. Optical and IR color-magnitude diagrams of the halos of the giant early type galaxy NGC 5128 (Cen A) obtained with *HST* (Soria et al. 1996; Minniti et al. 1999b).

to resolve distant elliptical galaxies into stars. In order to do this, it is desiderable to move into the near-IR. New HgCdTe and InSb arrays deliver high quantum efficiency over a large wavelength range. There are clear advantages of the near-IR in stellar population studies, as outlined by Silva (1996) and Bedding et al. (1997): (i) Giant stars have the peak of their spectral energy distribution at $1-3\mu$m, providing higher contrast relative to the underlying fainter stars; (ii) Dust extinction is reduced ($A_K = 0.1 A_V$); (iii) The transformation between the photometric observations and theory (Lbol, Teff) is simpler in the IR than in the visible; (iv) IR colors avoid the degeneracy of the red giant branch that optical colors suffer (Bica et al. 1991). This degeneracy makes it difficult to determine ages or metallicities solely from optical photometry, especially for the more metal–rich populations that dominate bulges and ellipticals.

Adaptive optics in the IR will give two additional benefits (Bedding et al. 1997). Firstly, it allows a substantial gain in sensitivity for point-source photometry by reducing the diameter of stellar images, thus increasing the signal relative to the background sky. Secondly, the increased resolution reduces confusion in crowded regions.

We cannot resolve galaxies into stars as far as we want, because of crowding, limited pixel size of the detectors, and other problems like contamination from the Milky Way and background galaxies. The line of sight to distant objects goes through the halo of our Galaxy, which contains many low mass stars. These can be estimated down to very faint magnitudes using simple Galactic models, and turn out not to be important in comparison with the contamination by background galaxies, which dominates at very faint K magnitudes.

4.1. *Resolving Distant Galaxies into Stars: NGC 5128*

The nearest example of a giant E-type galaxy is NGC 5128. This galaxy is located at D = 3.6 Mpc, determining that only the upper giant branch is observable. NGC 5128 has been resolved into stars with *HST* in the optical (Soria et al. 1996), and in the IR (Minniti et al. 1999). New *HST* optical-IR color-magnitude diagram obtained with *HST* and NICMOS+WFPC2 are shown in Figure 5. This figure illustrates some of the advantages of the near-IR, namely better foreground discrimination and wider color baseline to measure abundances. These studies agree in that the NGC 5128 halo is predominantly old and metal-rich, as are the stellar populations found in the Milky Way bulge (see Chiappini 2001).

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