A PANORAMIC VIEW OF THE MILK WAY ANALOG NGC 891

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ABSTRACT

Recent panoramic observations of the dominant spiral galaxies of the Local Group have revolutionized our view of how these galaxies assemble their mass. However, it remains completely unclear whether the properties of the outer regions of the Local Group large spirals are typical. Here, we present the first panoramic view of a spiral galaxy beyond the Local Group, based on the largest, contiguous, ground-based imaging survey to date resolving the stellar halo of the nearest prime analog of the Milky Way, NGC 891 (D ≈ 10 Mpc). The low surface brightness outskirts of this galaxy are populated by multiple, coherent, and vast substructures over the ∼90 kpc × 90 kpc extent of the survey. These include a giant stream, the first to be resolved into stars beyond the Local Group using ground-based facilities, that loops around the parent galaxy up to distances of ~50 kpc. The bulge and the disk of the galaxy are found to be surrounded by a previously undetected large, flat, and thick cocoon-like stellar structure at vertical and radial distances of up to ~15 kpc and ~40 kpc, respectively.

Key words: galaxies: halos – galaxies: individual (NGC 891) – galaxies: stellar content

Online-only material: color figure

1. INTRODUCTION

In recent years, it has been increasingly recognized that many of the clues to the problem of galaxy formation are preserved in galaxy outskirts (e.g., Johnston et al. 2008, and references therein). The current consensus is that large spirals begin as small fluctuations in the early universe and grow by in situ star formation and hierarchical merging (e.g., White & Rees 1978). Subsequently, once a spiral is the dominant component in such mergers, it continues accreting and disrupting sub-halos falling into its potential well. With the accumulation of accretion and disruption events, massive spirals build up stellar and dark matter halos (Abadi et al. 2006). The complete disruption of the sub-halos may take several orbits, distributing thus the tidally stripped stars over a broad range of distances from the main galaxy. As galaxies are predicted to assemble their outskirts from the disruption of a large number of satellites, these regions are expected to possess significant density and chemical substructures (Font et al. 2006).

Observationally, however, the nature and the origin of those regions remain elusive. Much of what we know about their properties is based on observations of the Local Group massive spirals (e.g., Freeman & Bland-Hawthorn 2002, and references therein). Recent surveys find evidence that the Galaxy stellar halo is divisible into two components, with a moderately flat inner regions showing a modest prograde rotation, whereas the outer regions are less chemically evolved and exhibit a nearly spherical distribution with a retrograde rotation (Carollo et al. 2008). Wide-field imaging data indicate that the stellar halo of the Galaxy is highly structured (Ibata et al. 2003; Yanny et al. 2003; Belokurov et al. 2007), suggesting that a large fraction of the halo has been accreted from satellites (Bell et al. 2008). The outer regions of Andromeda have been recently observed to contain even more substructure and streams than observed around the Milky Way (Ibata et al. 2007), suggesting that its accretion history may have been more active than the suspected quiet one of the Milky Way (Mouhcine et al. 2005a; Hammer et al. 2007). It is completely unknown however if these properties are generic features of the outskirts of spirals, or are reflecting peculiar assembly histories.

We have seen recently a dramatic progress in large-scale mapping of the Milky Way and Andromeda, with a number of large surveys measuring photometric, kinematic, and chemical properties of individual stars over a wide galactic volume. Although those surveys will significantly advance our understanding of the assembly of these galaxies, it cannot be assumed that a sample of two galaxies will provide the definitive solution to the nature and origin of the stellar content in the outskirts of spirals. The fundamental next step to fully exploit the Local Group surveys and thereby to establish a comprehensive picture of the assembly histories of spirals is to determine whether the Local Group massive spirals are suitably typical by studying giant spirals beyond the Local Group.

A number of surveys of the low surface brightness outskirts of spirals beyond the Local Group have been conducted recently. These surveys were however either sampling-limited galactic volumes (Mouhcine et al. 2005b, 2007; Bland-Hawthorn et al. 2005; de Jong et al. 2007), or too shallow to detect the old stellar tracers (Davidge 2006, 2007), thus severely hampering their impact. Measurements of galaxy outskirts have been also attempted using integrated light (Morrison et al. 1994), and have succeeded on detecting low surface brightness tidal streams in the outskirts of a few nearby disk galaxies (Martinez-Delgado et al. 2008, 2009). Those measurements are however affected by large uncertainties (de Jong 2008; Martinez-Delgado et al. 2008), and are able to detect stellar structures down to a surface brightness limit of μt ∼ 28 mag arcsec−2 at the faintest (Zheng et al. 1999), many magnitudes brighter than the bulk of substructure detected in the outskirts of the Local Group spirals (Belokurov et al. 2007; Ibata et al. 2007).

Characterizing comprehensively the outskirts of spirals beyond the Local Group requires resolving panoramically the stellar content of those regions, giving access to the extremely low
surface brightness structures. The required observations are, however, extremely challenging due to the photometric depth one has to reach, i.e., $I \sim 26$–$28.5$, to resolve old giant stars in galaxies beyond the Local Group, restricting this approach (using the present-day instrumentation) to the small number of spirals closer than $\sim 10$–$12$ Mpc.

Because the theoretical predictions are inherently statistical in nature, and due to the stochastic nature of halo formation, constraining the assembly history of galaxy outskirts must rely in large part on measuring the demographics of their stellar populations. To this end, we have initiated a survey to resolve panoramically the stellar content of galaxy outskirts for a sample of nearby, i.e., up to $\sim 10$ Mpc, highly inclined spirals, distributed over a broad range of masses, i.e., circular velocities ranging from $\sim 80$ km s$^{-1}$ up to $\sim 230$ km s$^{-1}$, and morphologies, i.e., ranging from Sa to Sd.

As part of this effort, we have targeted the edge-on galaxy NGC 891, often considered as the nearest prime analog of the Galaxy. Our group recently used deep optical imaging data, obtained with the Advanced Camera for Surveys on board the Hubble Space Telescope (HST/ACS), to investigate the properties of the resolved extra-planar stellar populations over the southeast quadrant of NGC 891, extending up to $\sim 10$ kpc from the galactic plane (Mouchine et al. 2007; Ibata et al. 2009; Rejkuba et al. 2009; Harris et al. 2009). Succinctly summarized, those studies indicate that the thick disk of NGC 891 shares comparable structural and chemical properties to its Galactic counterpart. The stellar populations beyond the thick disk appear to possess significant small-scale variations in the stellar metallicity. Interestingly, those regions are found to be dominated by stars significantly more chemically enriched than those populating the regions of comparable heights from the plane of the Galaxy.

In this Letter, we report the first results of our survey. Detailed analysis of the properties of the stellar content of different galactic components, the search for substructures, the determination of metallicity distribution functions and their spatial variation, and the properties of the globular cluster system will be reported in forthcoming papers. The layout of this Letter is as follows. In Section 2 we present briefly the data set. In Section 3 we report the discovery of new morphological structures around NGC 891, and discuss the implications of our finding for the formation and evolution of spiral galaxies.

Throughout the Letter, we use an intrinsic distance modulus for NGC 891 of $(m - M)_0 = 29.94$, with the tip of the red giant branch (RGB) located at $I = 25.84 \pm 0.04$ mag (Mouchine et al. 2007; Tikhonov & Galazutdinova 2005). NGC 891 is located at relatively low Galactic latitude ($\ell = 140^\circ 38^\prime$, $b = -17^\circ 42^\prime$), and therefore suffers from significant (though not large) extinction from foreground dust: $E(B - V) = 0.065$ (Schlegel et al. 1998).

2. DATA

The Subaru Prime Focus Camera (Suprime-Cam) on the 8.2 m Subaru Telescope is a mosaic camera of 10 chip 2048 $\times$ 4096 charge-coupled devices, which covers a 34 arcmin $\times$ 27 arcmin field of view with a pixel scale of 0.20 arcsec (Miyazaki et al. 2002). The instrument was used to image the outer regions of NGC 891. In the following, we will describe briefly the observations and the data reduction; the full details will be reported elsewhere.

The observations were taken in the Johnson visual $V$ band and Gunn $i$ band. We have obtained a total of 10 hr of good quality data in the $V$ band and 11.27 hr in the $i$ band, with seeing better than 0.6 arcsec, allowing us to resolve approximately the brightest two magnitudes of the RGB of metal-poor stellar populations at the distance of NGC 891. By covering a vast $\sim 90$ kpc $\times$ 90 kpc region around NGC 891, the survey allows us to distinguish local density enhancements from large-scale structure of the halo of the galaxy and/or the foreground distribution of stars.

The images were pre-processed using the Cambridge Astronomical Survey Unit photometric pipeline. The final stacks were created by summing all pixels, weighted by the estimated seeing on each frame. The DAOPHOT/ALLSTAR software suite (Stetson 1987) was used to detect all sources down to 3$\sigma$ above the sky. Isolated bright stars were identified over the frame to serve as point-spread function (PSF) templates. The PSF was modeled as a Moffat function; experiments showed that allowing the PSF to vary spatially over the field did not improve significantly the fit to bright stars, so we adopted a spatially constant PSF. Finally, the instrumental magnitudes were shifted to agree with the calibrated photometry presented in Rejkuba et al. (2009).

The analysis of the photometric errors indicates that the average $i$-band error varies from $\sigma_I \approx 0.05$ at $i \approx 25.8$–$26.0$, i.e., the bright end of the RGB, to $\sigma_I \approx 0.15$ at $i \approx 26.8$–$27.0$, i.e., approximately a magnitude below the tip of the RGB, while the average color error varies from $\sigma_{i(V-i)} \approx 0.12$ to $\sigma_{i(V-i)} \approx 0.18$ within the same magnitude range. To estimate the photometric completeness of the survey, we used the artificial star simulations performed for our analysis of the HST/ACS deep images of NGC 891, and described in full detail in Rejkuba et al. (2009). By comparing directly the number of stars detected in both HST/ACS and Supreme-Cam images as a function of magnitude and spatial density of RGB stars, it is possible to compute the photometric completeness of our survey. For stars located above $\sim 6$ kpc from the galactic plane, i.e., regions where the crowding is not at all important (see Rejkuba et al. 2009 for more details), the data are well above $\sim 80\%$ complete for the upper 1 mag of the giant branch, i.e., $i \lesssim 27$.

Objects were classified as artifacts, galaxies, or stars according to their morphological structure on the images. The point source catalog consists of NGC 891 RGB stars, NGC 891 asymptotic giant branch (AGB) stars, Galactic foreground stars, and unresolved background galaxies. In order to isolate stars to probe the spatial distribution of the stellar populations in the outskirts of NGC 891, we applied a series of magnitude and color cuts. RGB stars are defined as those with foreground extinction-corrected $i$-band magnitude fainter than 25.8 and brighter than 27, and with $(V - i)_c$ colors redder than 1.1, while AGB stars are selected as those with foreground extinction-corrected $i$-band magnitude ranging between 25.0 and 25.8 and foreground extinction-corrected $(V - i)_c$ colors redder than 1.2.

3. THE PANORAMIC LANDSCAPE AROUND NGC 891

Figure 1 shows the surface density map of RGB stars across the surveyed area. Numerous enhancements of the surface density of RGB stars are visible with the most striking being the large-scale complex of arcing loops and streams wrapped around the galaxy. About a half-dozen arc-like features are visible in the density map of old stars, extending up to $\sim 40$ kpc west and $\sim 30$ kpc east of the galactic stellar disk. On the left side, corresponding to the northeastern part of the galaxy, it is possible to trace the full extension of a giant loop turning around, falling toward the plane of the galaxy, and extending
Figure 1. Surface density map of RGB stars over the surveyed area around NGC 891. The over-densities of old RGB stars detected in the present study reveal a large complex of arcing streams that loops around the galaxy, tracing the remnants of an ancient accretion. The second spectacular morphological feature is the dark cocoon-like structure enveloping the high surface brightness disk and bulge.

Further to the south. The spatial density of AGB stars does not exhibit however any obvious enhancements associated with the large-scale complex of streams of old stars. Note that there is no evidence for a significant clumping in the distribution of extended sources across our field, Galaxy clusters and other large-scale structure are unlikely to dominate the counts at the angular scales of the observed features (Couch et al. 1993).

It is tempting to suggest that the large-scale network of old star streams is connected, originating from a single accretion event, however it is impossible to argue this firmly based on the stellar density map alone. Nevertheless, the arc-like features exhibit similar shapes, angular lengths, radii of curvature, separation from the parent galaxy, and levels of stellar density enhancements. In addition, the stellar loops appear to be distributed and to cross each other in a pattern strikingly similar to the classical rosette-shaped loops predicted for tidally disrupting dwarf galaxies in N-body simulations (e.g., Ibata & Lewis 1998; Law et al. 2005). These properties provide circumstantial evidence that the arc-like features around the galaxy may all come from a single accretion event (detailed modeling of the stellar stream will be presented elsewhere).

The discovery of the NGC 891 giant stream in the first deep, panoramic survey of the Milky Way’s nearest analog, together with the previous discoveries of tidal streams in the Milky Way, Andromeda, NGC 5907, and NGC 4013, suggests that halo substructure in the form of tidal streams may be a generic property of massive spirals, and that the formation of galaxies continues at a moderate rate up to the present day.

Figure 1 shows that the spatial density of old stars varies along the streams, however, nowhere among these features is there a region dense enough that it could be identified as the remaining core of the disrupted progenitor dwarf satellite. The stellar streams are most likely the fossil remnants of a totally cannibalized system, although the core of the disrupted satellite could possibly be hidden behind the disk of the galaxy. Deep radio observations of NGC 891 have reported the presence of a large gaseous filament and a number of counter-rotating clouds in its halo, extending to comparable distances from the disk as the stellar stream (Oosterloo et al. 2007). The structure and the kinematics of these gaseous structures appear to favor a scenario in which they are the results of a flyby interaction with the gas-rich satellite UGC 1807 (Oosterloo et al. 2007; Mapelli et al. 2008).

Figure 2. : $i_0$ vs. $(V - i)_0$. color–magnitude diagrams for a stream field (left panel) and an off-stream field (right panel). Superimposed on each panel are RGB tracks (shifted to the distance of NGC 891) of three Galactic globular clusters of different metallicities: M 15 ([Fe/H] = −2.2), NGC 1851 ([Fe/H] = −1.2), and 47 Tuc ([Fe/H] = −0.7) from Da Costa & Armandroff (1990).

(A color version of this figure is available in the online journal.)

The second striking feature visible in the surface density map of RGB stars is the extended super-thick envelope surrounding the galaxy. The defining high surface brightness components of a spiral, i.e., the bulge and the disk, are embedded in a vast flattened cocoon-like structure extending vertically up to ~15 kpc, and radially up to ~40 kpc, with a structure quite unlike any classical notions of thick disk or halo. This structure is strikingly flatter than the inner component of the Galactic halo that dominates out to ~10 kpc above the disk (Preston et al. 1991; Carollo et al. 2008). An additional highly flattened component of the Galactic halo has been recently detected (Morrison et al. 2009). This halo flat component is however suspected to be confined within very close distances from the Galactic plane (Preston et al. 1991; Morrison et al. 2009).

A stellar structure resembling the Galaxy thick disk has been resolved in NGC 891, with a vertical scale height of $h_Z \sim 1.45$ kpc (Ibata et al. 2009). Stars in this morphological structure show no metallicity gradients both vertically and radially, and
cover a wide range in metallicity, similar to what is observed for the Galaxy (Gilmore et al. 1995; Ivezić et al. 2008). However, at vertical distances larger than ~5 kpc from the plane of the galaxy, stars belong to a more extended structure (Ibata et al. 2009), and possess a negative metallicity gradient, albeit a mild one (Rejkuba et al. 2009). The envelope surrounding NGC 891 is therefore highly unlikely an extension of the thick disk. Thus, it appears that the flattened super-thick envelope surrounding the galaxy is a previously unknown component of NGC 891.

Our previous investigations of the properties of the stellar content of the southeast quadrant, sampling stars of the super-thick envelope, find strong evidence for large amounts of chemically distinct substructures (Ibata et al. 2009). This suggests that those regions are populated by numerous accretion remnants that are spread over a large volume and are still far from being fully phase mixed. Since it is natural to expect that the stellar populations in this quadrant are representative of those populating the super-thick structure, this indicates that the stellar structure surrounding the galaxy was assembled from the tidal disruption of many accreted satellites.

The super-thick structure presented here is not just a peculiarity of NGC 891: a preliminary analysis by our group of deep panoramic observations of the nearby edge-on galaxy NGC 2683 clearly shows the presence of an almost identical structure surrounding the high surface brightness components of that galaxy. Detailed kinematical measurements have revealed that a number of stellar substructures present at large radii of Andromeda corotate with the inner stellar disk, and are distributed in a gigantic flattened “extended disk” structure, extending radially from the high surface brightness inner disk out to ~40 kpc from the galaxy center (Ibata et al. 2005), i.e., strikingly similar to the radial extent of the super-thick stellar structure surrounding NGC 891. Given that we do not observe Andromeda edge-on, it is possible that the “extended disk” in that galaxy has a similar vertical extent to the new morphological structure identified in NGC 891 and NGC 2683.

The debris resulting from the disruption of a dwarf galaxy on a prograde orbit that is coplanar with the host galaxy disk is expected to relax into an extended rotating disk (Penarrubia et al. 2006). The detection of the Monoceros stream in the Galaxy (Yanny et al. 2003; Ibata et al. 2003), the presence of an extended disk around Andromeda (Ibata et al. 2005), and the stellar stream around NGC 4013 (Martinez-Delgado et al. 2009), all suspected to be the remnants of the disruption of satellites moving in low inclined orbits, suggest that the accretion of satellites on low-inclination and low-eccentricity orbits may be a relatively common process in the formation of spirals (Pohlen et al. 2004). Numerical simulations in the framework of the hierarchical cold dark formation scenario predict that large spirals experience several mergers of dwarfs with masses ranging from 1% to 10% of the host mass (Gao et al. 2004), with many on low-eccentricity orbits (Ghigna et al. 1998). The present work suggests that a super-thick stellar envelope formed by numerous accretions may be a common feature of large spirals.

This work is based on data obtained at the Subaru Telescope, operated by the National Astronomical Observatory of Japan.