Good Science with Modest Instruments

R. Jay GaBany
Blackbird II Observatory, Alder Springs, California
rj2010@comcast.net

David Martinez-Delgado
Max Planck Institut fur Astronomie, Heidelberg, Germany
delgado@mpia-hd.mpg.de

Abstract

An ongoing collaboration between the authors and an international team of professional astronomers has demonstrated the scientific potential of using modest aperture, commercially produced, semi-robotic telescopes situated under steady dark skies and affordable off-the-shelf astronomical cameras to reveal extremely dim, diffuse structures on the outskirts of distant galaxies that sheds light on galactic evolution. In this paper, we share our techniques, experiences and highlights of our investigations thus far.

1. Introduction

Within the hierarchical framework for galaxy formation, merging and tidal interactions are expected to shape large galaxies up to the present day. While major mergers are quite rare at present, minor mergers and satellite disruptions - that result in stellar streams - should be common, and are indeed seen in both the Milky Way and the Andromeda Galaxy.

As a pilot study, we have already carried out ultra-deep, wide-field imaging of some spiral galaxies in the Local Volume and revealed external views of such stellar tidal streams with unprecedented sensitivity and detail based on data taken with modest robotic telescopes (0.1-0.5-meter).

We have since embarked on a project that undertakes the first systematic and comprehensive imaging survey of stellar tidal streams from a sample of ~60 nearby Milky Way-like spiral galaxies within 15 Mpc having a surface brightness sensitivity of ~29 mag/arcsec.

Once completed, the survey will result in estimates of the incidence, size/geometry and stellar luminosity/mass distribution for each stream. This will not only to put the Milky Way and M31 in context, but provide the first extensive statistical basis that can be compared with state-of-art, self-consistent Lambda ΛCDM cosmological simulations of this phenomenon. The results of the project will provide a direct and stringent test of Hierarchical structure formation on this scale, constrain the present-epoch (minor) interaction rate and probe the minor-merger resilience of stellar disks.

The survey is being performed with modest telescopes and off the shelf cameras that are readily available from commercial and retail sources.

This paper describes the initial results of our pilot study on several nearby spiral galaxies. These systems were selected for the study because they were already suspected of being surrounded by diffuse-light over-densities based on data collected from available surveys (e.g., POSS-II; SDSS-I) and previously published deep images posted on the Internet by amateur astronomers.

While based on a biased sample of systems preselected for substructures, our pilot study served as a proof of concept for the more systematic survey of halo substructure around spiral galaxies that we have already commenced. It also enabled us to resolve the required observing strategies and data reduction methodologies. The results presented here come from a productive collaboration between amateur and professional astronomers, dedicated to exploiting the scientific potential of modest aperture telescopes.

2. Instrumentation and observational methods

The first tidal streams surrounding the Milky Way were discovered early last decade. Their detection resulted from the first large scale digital mapping projects, such as the Sloan Digital Sky Survey-1 (SDSS-1) and the Two Micron All Sky Survey (2MASS).

Due to their proximity, these structures are easily resolved into individual stars through professional two-meter class telescopes. Unfortunately, our internal perspective and the low surface brightness of these huge structures complicate our efforts to trace and build accurate models about their formation.

Detecting these faint features requires very dark sky conditions, the right choice of instruments, a thoughtful observing strategy, and appropriate data reduction schemes. Improper flat-fielding, sky subtraction or de-fringing makes their detection much more difficult or even impossible. Also by most estimates, the Milky Way's stellar streams create a five to ten degree wide, 360-degree arc across the entire sky. These enormous dimensions, limited observing time on professional telescopes and the restricted view of their cameras make a systematic study prohibitive

Tidal streams around other spiral galaxies offer different challenges to those surrounding the Milky Way. Stellar tidal streams around nearby galaxies cannot be resolved into stars and thus appear as elongated diffuse light regions that extend over several arc minutes as projected on the sky. Their typical surface brightness is ~27 mag arcsec or below, depending on the luminosity of the progenitor and the time they were accreted (Johnston et al. 2001).

While their apparent size fits within typical sensor fields, their distance necessitates long exposures to gather data with acceptable signal to noise. Again, competition for professional telescope time results in limited access that precludes extended observations.

Recent advances in the sensitivity of production CCD chips, the trend toward larger aperture private telescopes in remote, dark sites and the freedom of use experienced by amateur astronomers led the team to consider the inclusion of a non-professional member. So, in 2006, we initiated a project to find stellar streams surrounding nearby spiral with modest robotic instruments located in the United States and Australia.

This pilot survey was conducted with privately owned observatories equipped with modest-sized telescopes. Each observing site featured very dark, clear skies with seeing that is routinely below 1.5 arcsec.

Both of the pilot survey telescopes described in this paper was located in the south central Sacramento Mountains of New Mexico at an altitude of ~2,225 meters above sea level. One was housed in the Blackbird Remote Observatory (BBRO) and the other was maintained by a commercial observatory service provider called New Mexico Skies.

The BBRO telescope was manufactured by RC Optical Systems and follows a classic Ritchey–Chretien design. This truss-mounted telescope features a .5 meter primary operating at f/8. It has a 27.7' x 18.2' field of view and a plate scale of 0.45" pixel when used in conjunction with its SBIG STL11000 astronomical camera (described below).

Figure 1. The .5 meter telescope at Blackbird Remote Observatory manufactured by RC Optical Systems.

We also made use of a wide field instrument for those galaxies with an especially extended angular size (e.g., NGC 5055). For this purpose, we selected the Astro-Physics Starfire (APS) 160EDF-6, a short focal length (f/7), 16 cm aperture refractor that provides a FOV of ~74 × 110 arcmin.

Figure 2. An Astro-Physics Starfire 160EDF- 6 wide field telescope.

Both instruments and associated equipment required to operate them were commanded with on-site control computers that allowed remote operation and control from any global location with high band width Web access. Each observatory used proven, widely available, remote desktop control software. Robotic orchestration of all observatory and instrument functions, including multiple target acquisition and data runs, was performed using available scripting software.

Each telescope is equipped with a commercially available CCD camera. The primary survey camera of the BBRO was the SBIG STL-11000, which uses a Kodak KAI-11000M imaging sensor. This sensor consists of a 4008 × 2672 pixel array with 9 × 9μm pixels and a plate scale of 0.45'arcsec per pixel. An identical camera was used with the wide field instrument.

Figure 3. SBIG STL-11000 astronomical camera

Our image sets consisted of multiple deep exposures with a non-infrared clear, ir-blocked luminance, a red, a green and a blue filter from the SBIG Custom Scientific filter set. The science images were reduced using the standard procedures for bias correction and flat-fielding. A master dark and bias frame was created by combining 10 dark sub-exposures each produced at the same exposure length and camera temperature settings used for the luminance and the filtered images. A master flat was produced by combining 10 separate sky flats at exposures for each filter. The red, green and blue filtered exposures were separately combined (using a median procedure) to produce red, green and blue master images that represented the total exposure time for each color filter. The master images for each filter were subsequently summed to produce a synthetic luminance image that represented the total exposure time of all the color filter data. It should be noted that the exposure lengths represented by each master color channel image were timed to normalize the color characteristics of the CCD camera's primary imaging chip and thus produced a synthetic luminance image that very closely matched exposures produced with a clear filter. The synthetic luminance image was then combined (using a median procedure) with all the clear filtered luminance sub-exposures to increase the contrast of the diffuse light. The resulting final image thus represents the sum of all available CCD exposures collected.

Photometric calibration of the luminance filter (L) images is not currently available. So, to assess their depth and typical quality in terms of background and flat-fielding, we relied on images of five of our galaxies- NGC 1084, NGC 3521, NGC 4216, NGC 4651, and NGC 5866- obtained by the Sloan Digital Sky Survey (SDSS; York et al. 2000; Data Release 7; Abazajian et al. 2009). Based on SDSS photometry, we derived photometric equations to convert the L-band counts into g-band magnitudes.

SDSS image mosaics were constructed as described in Zibetti et al. (2009) and high S/N, g - L color maps of these galaxies were obtained with adapt-smooth (Zibetti 2009). Using these maps, we estimated the median zero point and the amplitude of the color terms, which turns out to be of the order of 0.1 mag, at most.

There are two main limitations to the depth that can be reached in imaging low-surface brightness features: (1) photon noise and (2) background fluctuations due to flat-field residual, internal reflections, ghosts, scattered light, etc. We estimate the photon noise limit as the surface brightness corresponding to five times rms in 2” diameter random apertures. For background fluctuations, we estimated the median sky level rms in selected boxes, several tens to hundred arcsec per side, spread around the galaxies. We find that the typical 2" diameter detection limit is 27.2 ± 0.2mag_g arcsec^{-2}, while the typical background fluctuations correspond to 28.5 ± 0.52mag_g arcsec^{-2}. It is worth noting that for the corresponding SDSS g-band images we measured 25 and 28.7, respectively. This shows that our images are roughly ten times deeper than the SDSS data in terms of photon statistics and are mainly limited by systematic background uncertainties, which are comparable to those of the SDSS data. This implies that our images have high efficiency in detecting sharp or localized features but background fluctuations hamper our ability to accurately measure smooth diffuse light.

3. Selected Observations

3.1 NGC 5907

NGC 5907 is a nearby spiral galaxy, about 35 million light years from Earth, which shares several characteristics with our home Galaxy: shape, absolute brightness and total mass. In 1998 a group of Chinese researchers, led by Dr. Zhaohui Shang, obtained deep images that first revealed the presence of a very diffuse elliptical ring in this galaxy's outer halo located about 160 thousand light years from the spiral's central region. This made NGC 5907 an ideal test for exploring the potential of amateur telescopes to detect galactic fossils in the outskirts of external galaxies.

Therefore, a series of observations were conducted between June and August 2006 that accumulated over 11.5 hours of exposure with the 0.5-meter BBRO telescope. The image shows that the ring discovered ten-years ago by Shang and his team is the most brilliant piece of a larger structure consisting of several ghostly diffuse arches surrounding NGC 5907. They were, most probably, produced by the tidal destruction of a satellite galaxy. (Smith et al. 2006). However, the image does not provide any hints on the position or final destination of the dwarf that produced the structure surrounding NGC 5907.

As discussed above, our search technique was designed to very clearly reveal the morphology of faint structures (for example, by combining all the available images obtained in different filters with the clear luminance deep images), but did not permit accurate photometry.

Therefore, follow-up photometric observations are needed to measure accurate surface brightness and to estimate the total luminosity of the detected tidal debris. Furthermore, the use of an uncalibrated luminance filter prevented us from estimating the surface brightness limit that we reached in our deep probe of the NGC5907 halo in any particular, standard photometric band. However, the detection of obvious diffuse light structures fainter than those reported in previous studies (with a surface brightness as faint as ~ 27.7mag_g arcsec^{-2}), suggests that our images reach a surface brightness magnitude fainter than the 27mag_g arcsec^{-2} limit of the deep NGC5907 image by Morrison, Boroson, & Harding (1994) and Sackett et al. (1994), and the 28:7mag_g arcsec^{-2} limited image by Zheng et al. (1999).

Figure 4. NGC 5907 and stellar streams captured by the .5m Blackbird Remote Observatory telescope.

3.2 NGC 4013

NGC4013 is one of the 62 luminous (M^B < −16.9) members of the Ursa Major cluster of galaxies, a nearby, late-type dominated, and low mass galaxy cluster. According to the HYPERLEDA database, the mean heliocentric radial velocity of NGC4013 (836 kms^{-1}) places it at a distance of 14.6 Mpc.

It is also a relatively isolated system, with the two nearest, slightly more luminous, cluster neighbors (NGC4051 and NGC3938) at ~170/250 kpc projected distance away. Classified as an Sb galaxy with a maximum observed rotational velocity of 195 kms^{-1} (Bottema 1996), an extinction corrected total absolute magnitude of -20.1 $_{Mabs\ Bband}$ Verheijen & Sancisi (2001), and an optical scale-length of 2.8 kpc (40") (van der Kruit & Searle 1982), NGC4013 is very similar to the Milky Way. NGC4013 is, moreover, famous for its prodigiously warped Hi disk, with a line of nodes close to parallel with that of the line of sight and with one of the largest warp angles observed (~25 deg).

We observed NGC 4013 with three different telescopes and instruments. In each case the same structures appeared, albeit with different degrees of clarity.

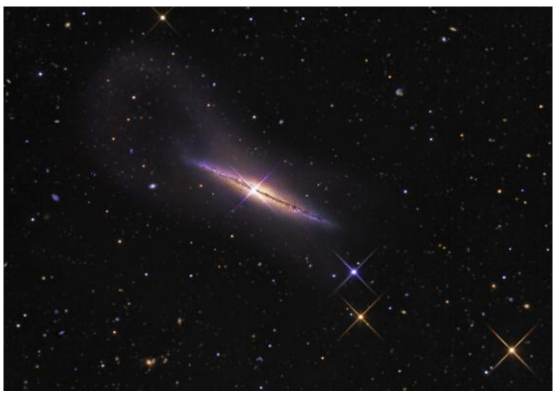

Figure 5. NGC 4012 and stellar stream captured by the Blackbird Remote Observatory .5m telescope.

3.2.1. KPNO 0.9m Telescope

NGC4013 was initially observed with the Kitt Peak National Observatory (KPNO) (now WIYN) 0.9-m, f/8 telescope as part of a pilot survey of low surface brightness features (like stellar tidal streams) around warped, nearby disk galaxies by C.P. and S.R.M. The initial sample included NGC3044, NGC3079, NGC3432 and NGC4013, all edge-on systems of large angular size with H1 warps but no nearby, massive companions (though, in the cases of NGC3432 and NGC3079, some associated or nearby low surface brightness or dwarf satellites). These disk systems resemble NGC5907, which at the time of this pilot survey had already shown to have a tidal loop by Shang et al. (1998), and, in the case of NGC3044, a minor merger was already hypothesized (Lee & Irwin 1997). Prior to the sample selection, we used the image filtering technique of Armandroff et al. (1998) on DSS2 images of several nearby, edge-on, warped disk galaxies to search for low surface brightness features indicative of potential streams. The image of NGC5907 produced in this way does reveal the brightest regions in that stream; however it is at extremely low signal to noise. The target galaxies for the KPNO observations were partly chosen because of structures in the filtered Digitized Sky Survey II (DSS2) images suggestive of potential streams, but in each case these were very low signal to noise features that did not provide incontrovertible proof of such a stream.

The observations were made with the Mosaic camera during several nights (UT 2000- 03-31 to 2000-04-04) using the "BATC 9" filter- essentially a narrow version of the Cousins R band- used by Shang et al. (1998) in their imaging of NGC 5907; the filter was kindly loaned by Rogier Windhorst. The conditions for this KPNO run were photometric, with a typical seeing of ~1.3". Using standard IRAF procedures for the overscan/bias correction and flat-fielding, we combined the final image of NGC4013 from the sum of four 1200 sec exposures, eight 1800 sec exposures, and one 900 sec exposure. A very faint arc is clearly identified in this image, situated at ~26' northeast of the center of the galaxy in the region of the extreme of northern plume of the gaseous warp (Bottema 1996, see Sec. 4). However, as may be seen, the achievable flat-fielding and surface brightness limit was not adequate to make definitive conclusions about the nature of this structure.

3.2.2. 2.5m Isaac Newton Telescope, La Palma

To confirm and better trace the extent of this structure, follow-up observations were obtained with the 2.5m Isaac Newton Telescope (INT) at La Palma using the Wide Field Camera (WFC) at f/3.29. This instrument holds four 4096'×2048' pixels EEV CCDs with a pixel size of 0.332", providing a total field of about 35'×35'. Images were acquired during two service nights (UT 2003-03-27 and 2003-04-03) using the Sloan r' (#214) and Harris B (#191) filters. From the first night we have two 600s r' band exposures and from the second night three additional 600s r' band images plus four 1350s B band exposures.

The central CCD (chip 4) was large enough (FOV 22.8'×11.4') to include NGC4013 and its warp, so we reduced only chip 4 in isolation, using standard IRAF procedures for the over-scan/bias correction, flat-fielding, and combining of the individual images. The background on the final B band image turned out to be reasonably flat, but the R band exposures suffered from scattered light causing large-scale variations in the background of the order of 2%. After careful masking of all sources, which were replaced by the mean of a linear interpolation along lines and columns, we used the IRAF imsurfit routine on a median filtered (~30" window) version of the masked and interpolated image to determine the background on each individual one. After subtracting this second order fit from the images they were combined to the final r' band version. The two images used in this study have an equivalent exposure time of 50min for the r' band and 90min for the B band. Due to the unstable weather conditions (high humidity, sometimes cirrus) during the two nights we did not use the observed standard stars, but obtained our photometric calibration from the r' and g' band Sloan Digital Sky Survey (SDSS) (York et al. 2000) by means of aperture photometry. After geometrically mapping the INT and SDSS images to the same scale and center and applying an identically-sized, but conservative (i.e. large) mask on the disturbing, bright star close to the center of NGC4013, we obtained fluxes in six concentric apertures (40"- 240"diameter) on all four images and so obtained the photometric zero-points for our INT images. The uncertainty is of the order of 0.01 mag. Following Smith et al. (2002) we converted the SDSS system to Cousins R and Johnson B and all the following magnitudes are given in R and B, correcting for Galactic extinction, (A_B = 0.072, A_R = 0.044; Schlegel et al. 1998), but not for inclination. Although the background is still an issue we can now more confidently trace and measure the low surface brightness arc.

3.2.3. Blackbird Remote Observatory .5m Telescope, New Mexico

Finally, we obtained very deep images of NGC4013 with the f/8.3 Ritchey-Chretien .5 meter telescope of the BBRO during different dark sky observing runs in the period UT 2006-11-06 though UT 2006-12-28. These data consist of multiple deep exposures through non-infrared clear luminance and red, green and blue filters from the SBIG custom scientific filters set. The images were reduced using standard procedures for bias correction and flat fielding. To enhance the signal-to-noise of the faint structures around NGC4013, the image noise effects were filtered by means of a Gaussian blur filter (Davies 1990).

3.3 NGC 5055 (M63)

NGC 5055 (Messier 63) is a large, relatively isolated Sbc-type galaxy (de Vaucouleurs et al. 1976) situated at a distance of 7.2 Mpc (Pierce 1994), and belongs to the Messier 51 galaxy group (Fouque et al. 1992). Its optical disk displays a fragmented and patchy pattern of spiral arms that extends outwards, resembling a celestial flower (hence its popular name: "The Sunflower Galaxy") which places it in the class of flocculent spirals (Elmegreen & Elmegreen 1987).

We recently reported the detection of low surface brightness features around NGC 5055 (Messier 63), including a large loop-like structure that is consistent with being part of a stellar tidal stream displaying ”great-circle" morphology (Johnston et al. 2008; Mart´inez-Delgado et al. 2010). This structure was first detected and speculated upon in a photographic study by van der Kruit (1979). The current work will show that this structure is consistent with being part of the ongoing evolution of Messier 63’s stellar halo. Along with the strong H1 warp, this feature is sound evidence for a recent interaction with a low-mass companion and becomes yet another example of the possible link between disk warps and recent mergers.

The discovery of faint structures around NGC 5055 (Messier 63) was made through the visual inspection of a deep, wide-field image obtained with a small 0.16 m telescope. In order to study this feature in more detail, we have observed Messier 63 with two additional telescopes and instruments for various purposes.

Figure 6. Stellar rings surround NGC 5055 in this view from the Blackbird Remote Observatory.

3.3.1. Blackbird Remote Observatory .5m Telescope, New Mexico

After the discovery of the low surface brightness features mentioned above, we confirmed their existence by re-examining a set of archived CCD images obtained during dark-sky observing runs in March and April of 2005 with the 0.5m f/8 Ritchey-Chretien telescope of the BBRO. As with the wide field telescopic data, the BBRO image set consists of multiple deep exposures (with individual exposure times of around 15 minutes) taken through the SBIG-Custom Scientific filter set.

3.3.2. McDonald Observatory 0.8m Telescope

Since the above observations yield only limited photometric information; we obtained follow-up observations using the McDonald Observatory 0.8 m telescope. These observations enabled us to characterize portions of the faint, outer structure and differentiate the tidal stream from other extended stellar halo and disk components.

The 0.8 m telescope uses a wide-field instrument, the Prime Focus Corrector (PFC), at f/3.0 (Claver 1992). This instrument features a front-side illuminated Loral-Fairchild 2048×2048 CCD with 15µ pixels that covers a 46.20 × 46.20 FOV at an image scale of 1.35500 arcsec per pixel. Deep images were acquired in B and R during a dark-sky observing run in April 2009. All on-sky images were taken at an airmass <1.6 and were dithered to reduce systematics. The observing conditions were generally very good; however, two nights had relatively variable transparency conditions.

The most striking feature in our deep images is the faint loop structure that apparently emerges from the East side of NGC 5055 (Messier 63)s disk and sweeps almost 180degrees to the North-East, reaching 14.00(~29 kpc projected) from the galaxy's center and entering again at the North-West side. When first discovered by van der Kruit (1979), there was little doubt that this feature was real. However, it was unclear if it originated in Messier 63 itself, or if it was rather "high latitude reflection nebulosity in our Galaxy" (i.e., Galactic cirrus), like that contaminating the field of Messier 81 and 82 (Sollima et al. 2010).

Our deep images hint that this feature is in fact part of Messier 63 based on similar morphology to the great-circle type tidal streams, arising from the disruption of a lower mass satellite galaxy in a nearly circular orbit.

3.4 NGC 4736 (M94)

We also conducted a deep multi-wavelength analysis (0.15–160 µm) to study the outer region of the nearby galaxy NGC 4736 (M94). We suspected the ring of material surrounding this galaxy might be more evidence of stellar streams. Instead, we found non-optical data supported the idea that the outskirts of this galaxy is not formed by a closed stellar ring (as traditionally claimed in the literature) but by a spiral arm structure.

In this sense, NGC 4736 (M94) is a good example of a Type III (anti-truncated) disk galaxy having a very bright outer disk. The outer disk of this galaxy contains ~23% of the total stellar mass budget of the galaxy and contributes ~10% of the new stars created showing that this region of the galaxy is active. In fact, the specific star formation rate of the outer disk (~0.012 Gyr-1) is a factor of ~2X larger (i.e. the star formation is more efficient per unit stellar mass) than in the inner disk. We have explored different scenarios to explain the enhanced star formation in the outer disk.

We found that the inner disk (if considered as an oval distortion) can dynamically create a spiral arm structure in the outer disk which triggers the observed relatively high star formation rate as well as an inner ring similar to what is found in this galaxy.

Figure 7. The extended spiral arms of NGC 4736(M94) seen in optical light by the BBRO telescope.

4. Discussion, future studies and conclusion

Our pilot survey of tidal streams associated with nearby galaxies has revealed that many spiral galaxies in the Local Universe contain significant numbers of gigantic stellar structures that resemble the features expected from hierarchical formation. Although we have only explored a handful of galaxies, our collection already presents a wide spectrum of morphologies for these stellar features. Some of them maybe have analogs in the Milky Way - e.g., (i) great arc-like features (labeled *A* in the last figure) that resemble the Milky Way's Sagittarius, Orphan and Anticenter streams (e.g., Majewski et al. 2003, Belokurov et al. 2006, 2007b, Grillmair 2006) and (ii) enormous clouds of debris that resemble our current understandings of the expansive Tri-And and Virgo overdensities and the Hercules-Aquila cloud in the Galactic halo (Rocha-Pinto et al. 2004, Belokurov et al. 2007a, Martinez-Delgado et al. 2007, Juric et al. 2008). Our observations also uncover enormous features resembling giant "umbrellas" (labeled *U* in the last figure), isolated shells, giant plumes of debris (labeled *GP* in the last figure), spike-like patterns (labeled S in the last figure) emerging from galactic disks, long, tightly coherent streams with a central remnant core (labeled *PD* in the last figure) and large-scale diffuse forms that are possibly related to the remnants of ancient, fully disrupted satellites.

Even when limiting the output of the simulations to a surface brightness comparable to our observational limit, the different stream morphologies seen fossilized in these nearby spiral halos can be easily identified in snapshots of the model halos as well. This is illustrated by in the last figure, which compares the most conspicuous types of tidal debris detected in our survey with those visible in the model snapshots for three different assembly histories. From an analysis of their models, Johnston et al. (2008: see their Fig. 1) concluded that the observed stream morphology is principally dependent upon the progenitor satellite's orbit and accretion epoch. For example, great circle features (like those seen around NGC 5907 and M63) apparently arise from near circular orbit accretion events that occurred 6-10 Gigayears ago. Straight narrow features with associated shells (e.g., the spikes in NGC 5866 and the umbrella shaped structure in NGC 4651, labeled *Sp* and *U* respectively in in the last figure) were formed in a similar epoch from low-mass satellites in almost radial orbits.

The tidal streams around external spiral galaxies are easier to study than those surrounding the Milky Way because our internal perspective places limitations on our view of streams associated with the Milky Way. Unfortunately, the search for tidal streams in the Local Group has not been completely successful- only six examples have been detected over the last decade. This result is not a complete surprise since the theoretical models predict the majority of spectacular structures have a low surface brightness and are located in the halo of spiral galaxies thus making their detection challenging with ground-based telescopes.

In 2006, we initiated a project to detect stellar streams with relatively small robotic telescopes located in the United States. Our collaboration started with a few images of spiral galaxy M94, obtained with a .5-meter telescope at the Blackbird Remote Observatory in New Mexico. These images displayed an amazing extended disk surrounding this nearby galaxy. One was arguably the deepest ever obtained and clearly demonstrated the scientific potential of modest instruments to detect very diffuse structures on the outskirts of distant galaxies.

We have since followed up with additional studies and confirmed the existence of tidal stellar steams around NGC 4013, NGC 5907. NGC 5055 and others (see the last figure)- all using modest instruments.

Encouraged by this pilot survey, we have embarked on the first systematic search for stellar tidal streams in a complete, volume limited sample of spiral galaxies up to 15 Mpc (i.e., the Local Volume). This will result in the first comprehensive census of stellar stream structures within the Local Volume and it will enable meaningful statistical comparisons with cosmological simulations. The frequency of streams, their stellar populations and their morphologies will help reveal the nature of the progenitors and lend insights into the underlying structure and gravitational potential of the massive dark matter halos in which they reside. This will thereby offer a unique opportunity to study the apparently still dramatic last stages of galactic assembly in the Local Universe. In this regard, the survey will be complementary to (and directly inform the interpretation of) local galactic `archaeological' data from resolved galaxies like M31 and the Milky Way.

Since objects within stellar streams continue to move along the satellite galaxy’s path, we have a chance to study the dwarf’s orbit seemingly frozen in the sky. This creates a set of conditions that would enable ten-meter class instruments, such as the Keck on Maua Kea or new Grantecam (GTC) at La Palma, to collect and measure the radial velocity of embedded stars, globular clusters and planetary nebula. These measurements would improve our understanding about the gravitational effect of spirals on nearby particles and improve models that probe one of the most profound galactic mysteries- their dark matter halos.

While waiting to collect information from large, professional telescopes, our statistical survey of tidal streams in local spiral galaxies will continue with modest amateur telescopes. These investigations demonstrate the potential of twenty-first amateur astronomers, armed with the latest technology, to participate in highly competitive international scientific projects.

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7. Figures

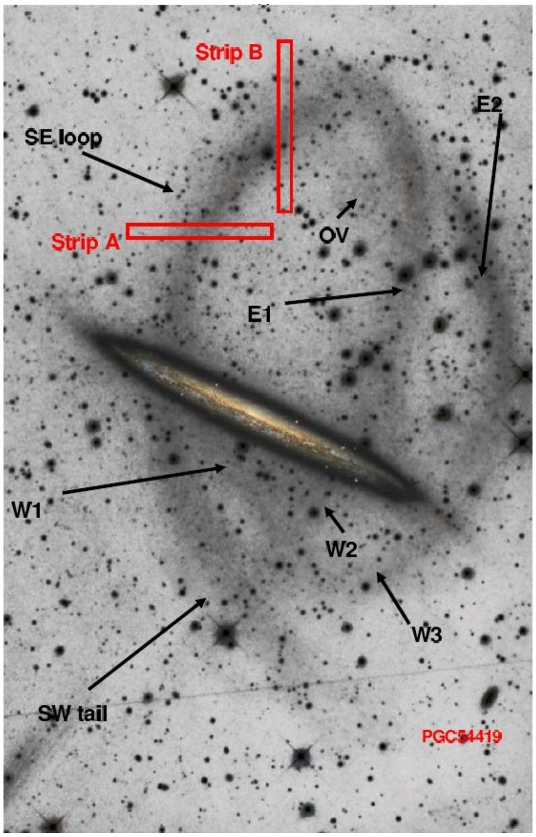

Figure 8. NGC 5907: This image displays identified photometric features detected in the data obtained with the BBRO .5m telescope. For reference, a color image obtained with the same telescope has been superimposed on the saturated disk region of the galaxy. The position of two different strips used to measure the width of the stream is also indicated by red rectangles. For comparison purposes, north is to the right and east is up.

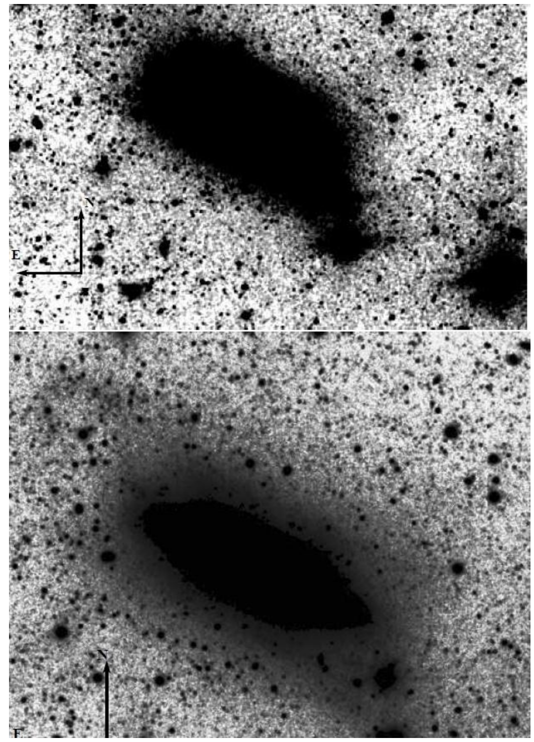

Figure 9. NGC4013: Smoothed and enhanced versions of the KPNO 0.9m image (upper panel) and the INT B band image (lower panel) highlighting the low-surface brightness features. The arrows of lengths 2' in the lower left corner give the size and orientation.

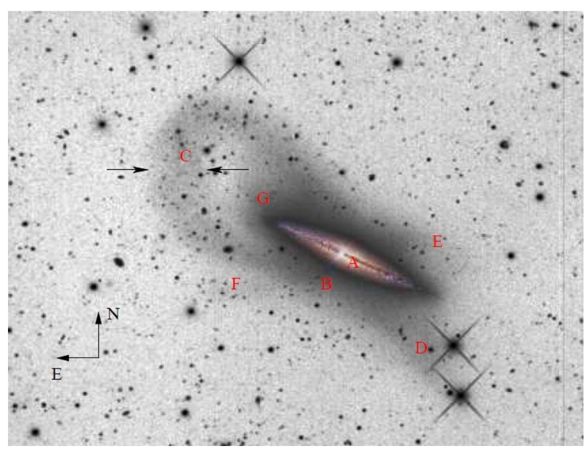

Figure 10. NGC 4013: This image was obtained with the BBRO .5m telescope. The total exposure time of the original image was 13.7 hours (including 11 hours through a clear-luminance filter) and was noise-filtered by applying a Gaussian blur filter. The image has dimensions of ~18.5' × 15', which, at the distance of NGC 4013 is ~78 × 63 kpc.

For illustrative purposes, a color image of the NGC 4013 obtained with the same telescope has been superimposed on the saturated disk region of the galaxy.

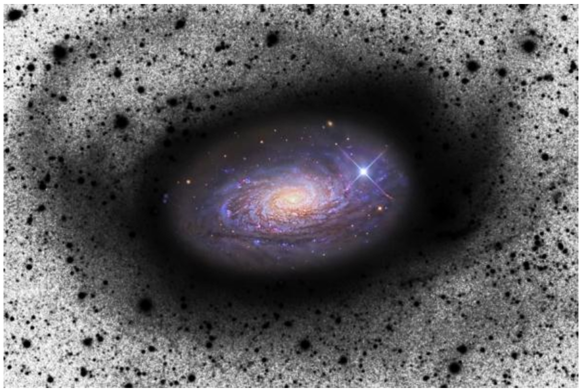

Figure 11. NGC 5055: The central portion is a positive image, the outer portions displays an inverted view so the faint structures are more apparent.

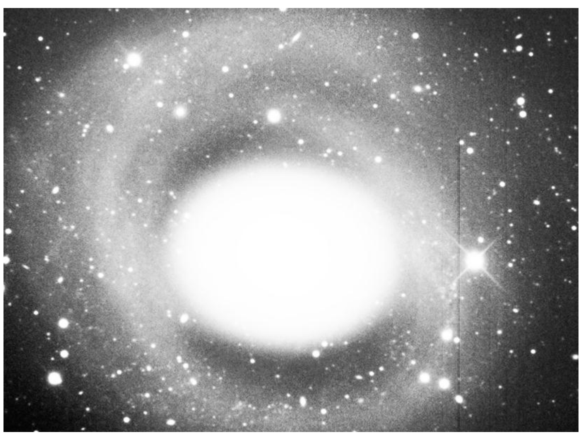

Figure 12. NGC 4736: This optical picture was produced when 90 separate exposures, obtained by the .5 meter BBRO telescope, were electronically combined to create a single image that's equivalent to a 13 hour exposure. When the variance between the dimmest and brightest parts of the image is extremely exaggerated, a process called 'super stretching', faint structures often jump into view.

Figure 13. NGC 4736 (M94): This picture was produced by combining mid wavelength infrared images from the Spitzer Space Telescope with near and far ultraviolet pictures from GALEX to provide a unique panchromatic view of NGC 4736 and its heretofore unsuspected outer spiral arms. Red, green and blue hues represent regions dominated by infrared radiation. Deep blue and yellow indicate areas with intensive ultraviolet emissions. Agua, violet and white result when areas overlap.

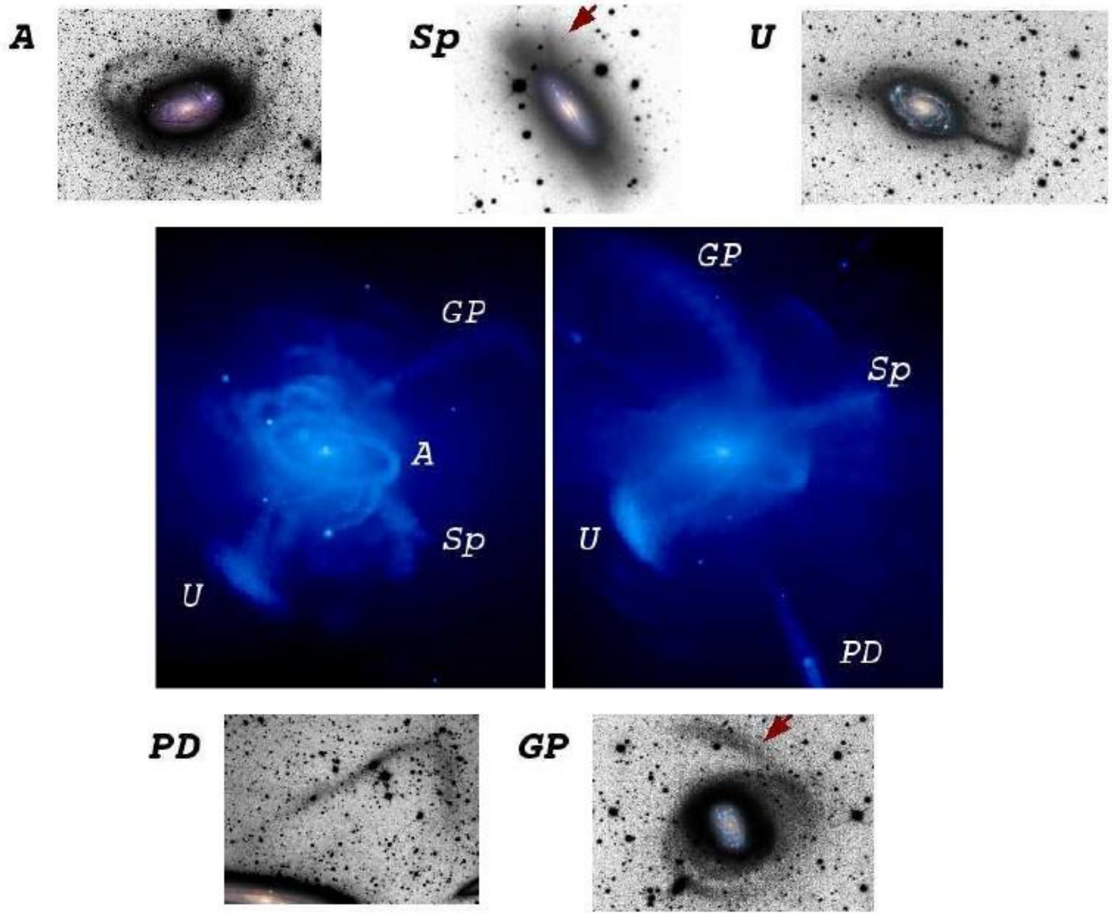

Figure 14. This is an illustrative comparison of some of the different features detected in our pilot survey to the surviving structures visible in cosmological simulations of Milky Way-like galaxies. The two central panels provide an external perspective realized through a simulation (from left to right, halo models numbered 17and 15 from Johnston et al. 2008) within the hierarchical framework and show luminous streams resulting from tidally disrupted satellites. Each snapshot is 300 kpc on a side.

The tidal features labeled in the snapshots identify structures similar to those observed in our data:

A: great circles features (Messier 63);
Sp: spikes (NGC 5866);
U: umbrella shaped structures (NGC 4651);
PD: partially disrupted satellites (NGC 4216);
GP: giant plumes (NGC 1084).