FOLLOW-UP OBSERVATIONS FOR M33 SATELLITE GALAXIES SEARCH

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ABSTRACT

M33 is predicted to host more than ten satellites galaxies, but only a single companion (And XXII) has been discovered to date. Is this a failure of galaxy formation models, or simply a by-product of how difficult it is to find low surface brightness galaxies in the nearby Universe? We propose to use the Hubble Space Telescope Advanced Camera for Surveys (ACS) instrument to obtain follow-up observations of the six most promising candidate dwarf galaxies identified with the Dragonfly Telephoto Array. The confirmation of even a single one of these companions will have a large impact in our understanding of cosmological and galaxy formation models. On the other hand, if some of these objects are found to be background ultra-diffuse galaxies with unusual colors or peculiar patches of cirrus, their observations can be used to further inform future searches. Determining the membership and nature of the candidate dwarf galaxies requires high-sensitivity imaging for which ACS is ideally suited.

1. SCIENTIFIC MOTIVATION

1.1. *Background*

Leading galaxy formation models portray a hierarchical system, where galaxies form in dark matter halos, and within these halos we find smaller sub-halos. As a consequence, we expect massive galaxies to host less massive satellites, and for these to host even less massive satellites, following the path down a hierarchy. The Triangulum Galaxy, or M33, is an excellent candidate for testing this idea, because it is both a satellite galaxy of M31 and the third most massive galaxy in the local group (van der Marel *et al.* 2019). A comprehensive analysis using numerical simulations predicts on the order of 10 satellites around M33 with stellar masses $M_* = 10^4 M_o$, a number consistent with expectations for other galaxies in the local group (Patel *et al.* 2018). It is surprising, therefore, that only a couple possible candidates have been found (Martínez-Delgado *et al.* 2021), and only one has been confirmed, And XXII (Martin *et al.* 2009).

In the case of M33, possible explanations for this shortage of satellite galaxies have been explored, including the possibility of a complex orbital history with its host, M31, that could have ejected the less gravitationally bound satellites of M33 (Semczuk *et al.* 2018). Dynamical models suggest, however, that M33's accretion is recent (van der Marel *et al.* 2019) and its satellites should have remained bound (Patel *et al.* 2017). The discrepancy between observed and predicted satellite galaxies is not unique to M33, as it is present in a multitude of observed systems. This brings up the question: Is this a result of a flaw in our leading cosmological and galaxy formation models, or is it a selection effect due to the difficulty of detecting faint sources? For the reasons outlines previously, further studying the M33 system can gear us into building a more robust answer to this question. Other motivations for studying dwarf galaxies are that they are predicted to host some of the oldest populations of stars (Skillman 2005) and potentially be the most dark-matter dominated objects in the universe (Simon and Geha 2007).

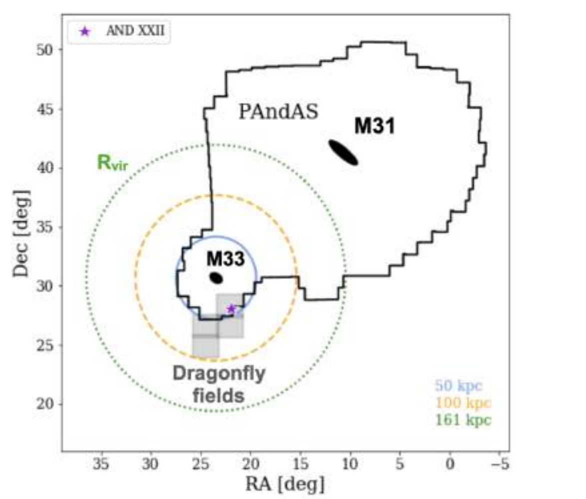

Fig. 1.— Visualization of our data and its location with respect to the Andromeda galaxy, M33, And XXII, and existing surveys of the area. The grey rectangles show the 4 fields that have been observed.

1.2. *Current efforts and the Dragonfly Telephoto Array*

M33's halo extends out to around 300 deg^2, as shown in Figure 1, so looking for the satellite companions of M33 requires covering a large survey area. On top of that, we expect that the satellite galaxies have very low surface brightness and low stellar densities (Simon 2019). Large reflector telescopes may not be suited for this purpose as they suffer from diffuse scattered light that limits the surface brightness depth. Figure 2 represents the problem we face. In particular, the middle panel is a g-band image taken by the Dark Energy Camera Legacy Survey (DECaLS) (Dey and et al. 2019) of the region surrounding And XXII, where, remarkably, the satellite galaxy is essentially invisible. The left panel shows the color magnitude diagram (CMD) of point sources around And XXII from the PAndAS survey (McConnachie *et al.* 2009). The overdensity in comparison to the reference background CMD eventually confirms the discovery of And XXII (Martin *et al.* 2009). While this confirmation using resolved point sources is undeniably effective, finding the candidate in resolved image in the first place would be non trivial and would require surveying a very wide area with a large telescope.

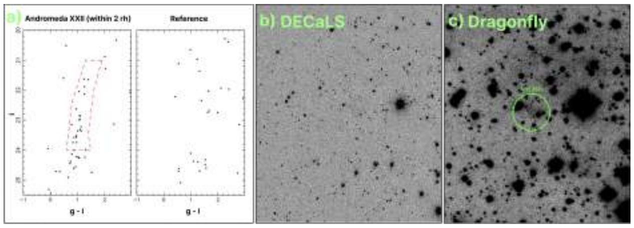

FIG. 2.— **a)** Color magnitude diagram of point sources around And XXII from the PAndAS survey (Martin *et al.* 2009) and in the reference background CMD. **b)** *g*-band image taken by the Dark Energy Camera Legacy Survey (DECaLS) of the region surrounding And XXII. **c)** Dragonfly *g*-band image of And XXII.

The development of new instruments and software pushes the boundaries of what we can observe. The Dragonfly Telephoto Array (hereafter Dragonfly in short) is optimized for the detection of relatively large low surface brightness sources (Abraham and van Dokkum 2014; Danieli *et al.* 2020a). Thus, surveying M33's halo with Dragonfly allows faint dwarf galaxies to be detected without having to resolve individual stars. The right panel of Figure 2 shows a Dragonfly *g*-band image of the same patch of the sky where And XXII is clearly detectable as an integrated light object.

To explore this potential, Dragonfly has observed four fields around M33, shown by the grey patches in Figure 1 for a total of 20 deg^2 in the *g*- and *i*- bands. From the calibrated, sky-subtracted images (Danieli *et al.* 2020b), we performed a series of data reducing steps to output a field where candidates could be efficiently spotted. As the satellite galaxies are expected to have a low surface brightness, the compact, bright sources in the fields were removed. This was accomplished using the Multi-Resolution-Filtering (MRF) software package developed by the Dragonfly team (van Dokkum *et al.* 2020). In addition, we don't anticipate that all remaining sources of extended emission are in fact satellite galaxies. Due to the relatively low galactic latitude of M33, our data is shaded by emission of light scattered from dust grains in our own galaxy (galactic cirrus) (Low *et al.* 1984). The dragonfly team has developed an algorithm to model and subtract the cirrus from the image *(Liu et al., in prep)* and its performance has exceeded expectations. Figure 3 shows the resulting field after MRF and cirrus removal. Note that compact sources have been removed, the brightest sources have been masked, and the cirrus (showing up as extended emissions mainly on the left side and bottom of the field) has been subtracted.

A careful inspection of the resulting fields revealed the presence of six promising candidate satellites. These objects were chosen after accounting for the context surrounding them and considering their apparent morphology in comparison to nearby patches of cirrus prior to removal. This is because though the cirrus removal works impressively well on large scales, we are not yet able to conclude that it removes all isolated patches of cirrus. The final candidates are shown in Figure 4, and their coordinates are given in Table 1.

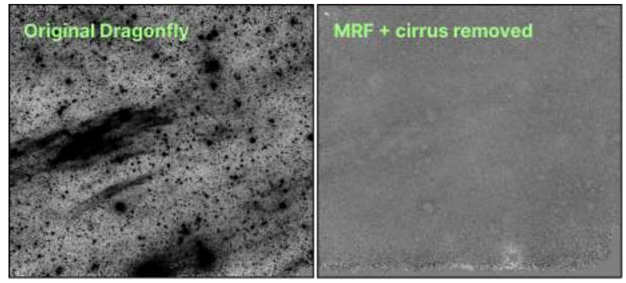

FIG. 3.— **Left:** Original Dragonfly *g*-band image of field #2. **Right:** Resulting image after performing MRF and cirrus removal on the same field. Notably, the compact high surface brightness sources have been removed and the cirrus was very successfully subtracted.

Candidate	RA	Dec
1	01:26:38.195	28:39:36.423
2	01:28:30.153	28:52:50.807
3	01:31:53.991	26:53:47.550
4	01:32:56.311	28:04:49.099
5	01:22:48.263	28:02:24.366
6	01:41:19.990	24:54:22.750

TABLE 1
COORDINATES OF M33 CANDIDATE SATELLITE GALAXIES TO BE OBSERVED.

1.3. *The need for HST data*

The combination of Dragonfly's capabilities and the successful performance of the MRF and cirrus removal algorithms turns the inspection process very effective. However, these low resolution observations only allow us to identify candidate galaxies. We now require follow-up observations to confirm any of these as real satellite companions of M33. As we have faint sources with low stellar densities, deep imaging with a high resolution is optimal, as it would make it possible to detect the presence of red giant branch (RGB) stars, pointing to the existence of a galaxy. In addition, resolving the tip of the RGB will allow us to accurately determine the distance to these galaxies and confirm their membership to the M33 system. We request, as described in the Technical Justification, a total amount of time of 241.2 minutes of ACS/WFC imaging to be shared between the F606W and F814W filters.

With this high resolution observation, we expect to resolve at least 30 RGB stars, sufficient for the overpopulation to be discriminated from the background. In addition, we expect we will be able to clearly define the tip of the RGB. **With this, the goals we hope to achieve are two-fold.**

1. Confirm the candidate satellite galaxies to be true low surface brightness dwarf galaxies.
2. Confirm their membership as companions of M33 based on their distances.

Some of the six candidates may be discovered to in fact be satellite galaxies of M33, which would be the more exciting outcome. Some may also turn out to be peculiar

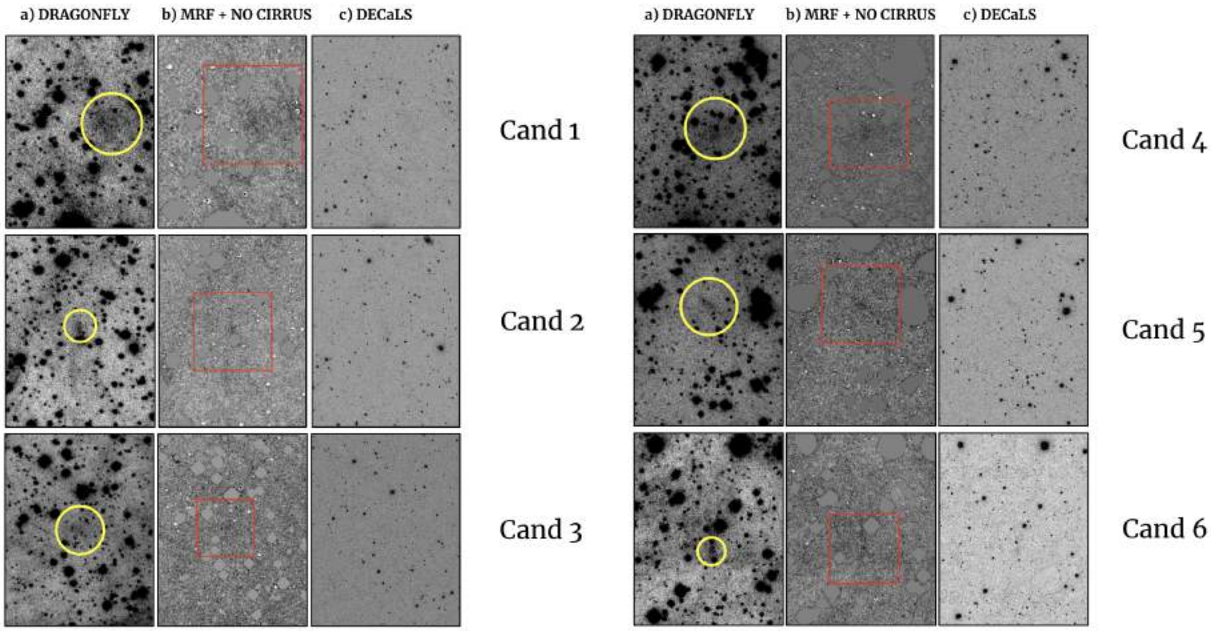

FIG. 4.— The six most promising candidates found in our four fields around the M33 halo. **Left:** original Dragonfly g-band image with the candidate circles in yellow. **Centre:** image after MRF and cirrus removal with the candidate enclosed in a red square showing the field of view of ACS/WFC. **Right:** high resolution DECaLS observation of the same region.

leftover patches of cirrus, ultra-diffuse background galaxies with unusual colours, or other objects. Regardless, the capabilities of the Dragonfly telephoto array with the newly developed tools by the Dragonfly team can hugely contribute to the exploration of questions set up earlier in the proposal. In combination with other instruments, such as the ACS/WFC, we hope that our efforts will lead to identifying M33 companions, but at the very least we will better understand the limitations and possibilities of our instruments and our approach.

2. TECHNICAL JUSTIFICATION

2.1. *Why HST ACS F606W and F814W bands?*

The goal of our project is to confirm and identify the nature of M33 satellite candidates through the search for spatially resolved stellar populations on the CMD. For a confirmation of the candidates as a true satellite of M33, we propose to use the ACS/WFC to resolve the tips of the RGB for each of these candidates. As seen in the left panel of Figure 2, a true satellite of M33 should trace a narrow band on the CMD. In addition, once the sources are resolved, the magnitude of the RGB tip can be used to derive the distances to these sources, thus confirming their membership to the M33 system (Müller *et al.* 2018). Due to the expected low surface brightness and low stellar densities, ground based observations face serious obstacles in performing at the degree of sensitivity required. Ground telescopes could resolve the stars, but the resolution would not reach the levels required. The tip of the RGB would not be resolved, and therefore the uncertainty on the distance estimates would be large, defying the purpose of confirming the membership of the satellites to the M33 system.

The Advanced Camera for Surveys (ACS) instrument, particularly the Wide Field Channel (WFC) present ideal capabilities for this purpose. The high resolution, sensitivity and wide field ensure that we can resolve the stellar population to a sufficient threshold of 5σ for the entirety of the source object. In addition, the proposed exposure times will ensure that the tips of the RGB are well defined, allowing for a deeper understanding of these sources and their membership to the system in discussion. The size of our selected candidates fits very well within the 202 x 202 arcseconds field-of-view of the ACS/WFC, as shown in Figure 4 by the red squares in the centre panels. The wavelength range is also fit for our needs. **We request observations with both the F606W and F814W filters for each of our six selected candidates.** The F814W filter can be used as an equivalent to the Johnson I filter, which is more commonly seen in studies of the CMD looking for RGB resolved stars. The F606W filter is chosen as it has a greater fractional photon detection efficiency (throughput) than the more typically used Johnson V (F555W) and provides enough separation from F814W.

2.2. *Exposure time and constraints*

The aim is to reach a 5σ depth for an RGB star with a magnitude 4 times higher than the tip of the RGB of M33. Results from (Martin *et al.* 2009) show this is around i 21.2 mag, so we are looking to resolve down to approximately i = 25 mag to a 5σ limit. If we assume the satellite galaxies have a similar metallicity to And XXII, then this corresponds to v 26 mag. For the exposure time calculation, we keep in mind the sky brightness (considering both zodiacal light and Earth shine) at wavelengths close to both the filters used as reported in the ACS instrument handbook. Assuming the detector efficiency to be 70%, **we estimate the required exposure time of 526 s with the F606W filter and**

680 s with the F814W filter.

We request two exposures to be done for each filter per target, with a dither offset of 20 arcseconds to eliminate possible systematics in individual exposures. **Each of the targets can be observed in both filters in one orbit.** Therefore, to observe the six dwarf satellite galaxies, **we request a total amount of time of 241.2 minutes of ACS/WFC imaging**. We expect that with this observation, at least 30 stars will be fully resolved, based on results from (Patel *et al.* 2018) shown in Figure 5. The proposed strategy couples the wide-field low surface brightness sensitivity of Dragonfly to the high-resolution deep imaging of the Hubble Space Telescope ACS/WFC instrument in order to search for companions to local group galaxies in an efficient and effective way.

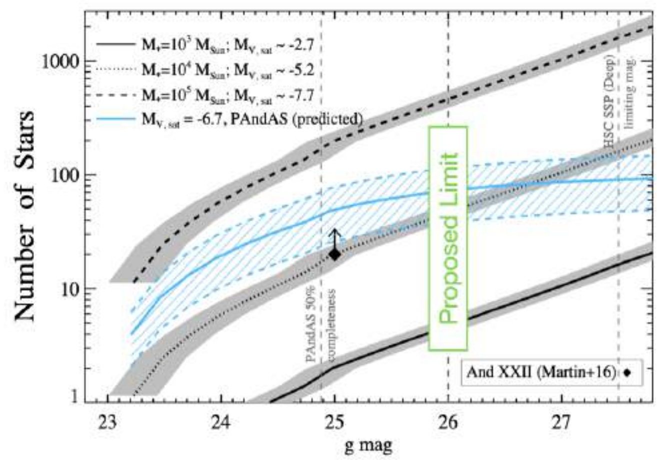

FIG. 5.— The expected number of resolved stars per satellite as a function of g-band limiting magnitude (Patel *et al.* 2018). The black lines indicates the number of resolved stars for satellites of different masses. The blue line shows the number of predicted number of resolved stars for a satellite similar to And XXII. Assuming the satellites have similar metallicities to And XXII, we expect to resolve 30 stars at our magnitude limits, sufficient to be discriminated from the background.

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