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CFHT [2008B - 2012B] Large Programs First Call

Deadline: 1 Feb 2008 - 24:00 UTC

Title	**The Pan-Andromeda Archaeological Survey (PAndAS): Tracing galaxy assembly in the near field**
Abstract	The Lambda-Cold Dark Matter hierarchical paradigm is robust to large scale observables, and it is on galactic scales that our understanding of the cosmological evolution of matter is most incomplete. Many of the predicted features of galaxies, such as faint satellites and diffuse stellar haloes, are extremely low surface brightness (> 31 mags per sq.arcsec). The Milky Way, M31 and M33 are therefore the only three large galaxies in the Universe which can currently provide robust tests of, and constraints on, many fundamental predictions of galaxy formation models. We propose the Pan-Andromeda Archaeological Survey (PAndAS), which will obtain g and i imaging of over 300 sq.degrees of the M31/M33 sub-group. PAndAS will provide the first panoramic view of galaxy haloes over a volume of ~15 million cubic kpcs, and will be complete to 32 - 33mags per sq. arcsec. PAndAS will provide the deepest and most complete panorama of galaxy haloes available, and will be used to compare to and constrain cosmological models of galaxy formation over an order of magnitude in halo mass. It will be unrivaled by any other extra-galactic wide field survey and will become a benchmark study of near field galaxy formation. The legacy value of PAndAS - for M31, M33, the Local Group, dwarf galaxies, globular clusters, stellar populations, galaxy formation and MW structure - is immense. It will become the primary reference dataset for all subsequent studies of the stellar populations of these galaxies, and will remain so into the era of Thirty Meter Telescopes and beyond. This survey is only possible for the M31/M33 sub-group, and it is only possible using the unique capabilities of CFHT/MegaPrime.
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Total number of **hours** requested: 226

Hours per agency:	Canada	France	Hawaii	Taiwan
	170	56		

Proprietary period for participating community access is zero by *default* (free immediate access).
If you want this proprietary period to be set to a specific time, provide below the time period and justification for the request.

Proprietary period for World Access is by *default* one year after the end of each semester for the duration of the survey.
If you want this proprietary period to be changed, provide below a data release schedule and a justification for the request.

Scientific Justification

I. Unraveling galaxy assembly in the near-field

Recent results have shown that the basic tenets of the Lambda-Cold Dark Matter (ΛCDM) cosmological paradigm are well understood and robust to large scale observables, such as the cosmic microwave background (Spergel et al. 2007) and galaxy clustering (Norberg et al. 2001). The past few years has seen the focus of cosmological studies shift into a new "precision" regime. Modern simulations of galaxy formation are very successful at using our current, incomplete, understanding of baryonic evolutionary processes to provide testable predictions about the small scale distribution of mass and light in and around galaxies. The onus, therefore, is to obtain data which will provide critical tests of the models on galactic scales and hence advance these important cosmological theories.

A natural consequence of galaxy formation in the hierarchical ΛCDM paradigm is that a typical $L_\star$ galaxy will accrete hundreds of smaller dark matter haloes over a Hubble time (t_H). Simulations predict not only the shape and profile of galaxy haloes (Navarro et al. 1995, 1996, 1997), but also the frequency, mass spectrum and radial profile of these substructures (Klypin et al. 1999; Moore et al. 1999; Diemand et al. 2007). In the classical halo formation model of Searle & Zinn (1978), the globular cluster (GC) population is formed through the accretion of proto-galactic fragments. In ΛCDM, the *entire* luminous halo is built from stars shed by merging sub-units (Bullock & Johnston 2005; Abadi et al. 2006), the progenitors of which have mostly since merged with the central galaxy. Unraveling the structure of the luminous haloes of galaxies is an important step towards unraveling the merger history of galaxies.

The highest resolution simulation of the formation of a galaxy halo to date - the *Via Lactea* simulation by Diemand et al. (2007) - has shown that the abundance of substructure closely co-evolves with the host halo, peaking near the epoch of turnaround and remaining constant once the region has virialised. The luminous material around galaxies are therefore remnants of, and clues to, the formation of the galaxy. Dynamical times in the outer halo are long ($> t_H$), and many accreted substructures will survive to the present without being totally tidally disrupted (Johnston et al. 1996). Even if many of these structures do not contain baryons (Bullock et al. 2000; Kravtsov et al. 2004), the outer halos of $L_\star$ galaxies should still host many luminous substructures. Their number, spatial distribution and morphology provides tests of structure formation and feedback on small scales; the metallicities and ages of their stellar populations reveal how star formation proceeds at early times and at the extreme faint-end of the luminosity function.

II. Resolving stellar haloes: Status of our M31/M33 photometric surveys

Simulations predict that stellar haloes formed though hierarchical merging have a power law profile of index $n = 3-4$, steeper than the dark matter, and that their overall shape reflects closely the mild triaxial distribution of the dark matter halo (Bullock & Johnston 2005; Abadi et al. 2006). Many of the luminous substructures predicted to exist in the host haloes have a surface brightness $\mu > 30\,\mathrm{mags\,arcsec}^{-2}$ (Bullock & Johnston 2005), and so cannot be detected through unresolved light. In contrast, resolved stellar population studies can reach $\mu > 31\,\mathrm{mags\,arcsec}^{-2}$. *M31, M33 and the Milky Way (MW) are the most accessible large galaxies in the Universe in which to probe such faint surface brightnesses*. For the MW, projection effects, (patchy) extinction and the gigantic survey area required means that these studies are not feasible for all but the largest all-sky surveys. The M31/M33 sub-group, however, provides a panoramic view of two large galaxies which span nearly an order of magnitude in host halo mass, and which subtend an area directly amenable to observations with CFHT/MegaPrime.

Our group has pioneered the study of the resolved stellar component of haloes with a survey of the inner haloes of M31 and M33 using the INT/WFC (Ibata et al. 2001; Ferguson et al. 2002; McConnachie et al. 2004; Irwin et al. 2005). We have since charted the south-east quadrant of M31's outer halo to a radius of 150 kpc using CFHT/MegaPrime from the French TAC between S03B – S06B (P.I. Ibata; Martin et al. 2006; Ibata et al. 2007; Figure S1) to obtain g and i imaging of giant stars more than 3 mags below the tip of the red giant branch (RGB). A Canadian extension to this survey to chart the south-west quadrant commenced in S06B (P.I. McConnachie); over half of this quadrant has now been observed and analysis is underway now that all calibration fields have been obtained (Figure S3).

Tidal streams: One of the most significant discoveries of our extant photometric surveys of M31 has been the discovery of a giant stellar stream (Ibata et al. 2001) which pollutes a significant fraction of the south-east quadrant of the halo (Ibata et al. 2007). Stellar population analysis shows that this extensive structure has a metal-rich core ($[\mathrm{Fe/H}] \sim -0.5$) and a metal-poor envelope ($[\mathrm{Fe/H}] \sim -1.1$), indicating its progenitor was a complex system; spectroscopic follow-up and dynamical modeling have placed its accretion time ~ 1 Gyr ago (Ibata et al. 2004; Fardal et al. 2007). Numerous other streams and over-densities with lower surface brightness have been detected (Ferguson et al. 2002; McConnachie et al. 2004; Chapman et al. 2008), including a huge tidal feature identified in preliminary analysis of the S06B data in the south-west quadrant. The individual and statistical study of these coherent structures - including spectroscopic and deep-imaging follow-up - are our primary handle on the properties of their long-disintegrated progenitors.

Dwarf satellites: We have found 5 new dwarf galaxies within the current survey limits at a signal to noise limit $S/N > 5$ (Martin et al. 2006; Ibata et al. 2007; Figure S2). Another 11 compact structures are seen down to $S/N \sim 3$, although these detections are marginal and are being followed-up with Subaru/SuprimeCam and HST/WFPC2. Spectroscopic observations have revealed that one of the new dwarfs is a very recent addition to the M31/M33 sub-group (Chapman et al. 2007), challenging our understanding of when and how it could have had time to develop its spheroidal morphology, which is thought to require prolonged interactions with massive host haloes (Mayer et al. 2006).

Globular clusters: The INT/WFC and CFHT/MegaPrime surveys have revealed a significant number of new GCs in the M31/M33 sub-group; we have almost doubled the number of clusters known beyond 1 degree from M31 using data from *only one quadrant* (Huxor et al. 2008), including finding a cluster at a projected distance of 120 kpc, by far the most distant M31 GC known (Martin et al. 2006). For M33, four new GCs have been discovered in the INT/WFC data. Many of the new M31/M33 GCs occupy a region of $M_v - r_h$ space in which there are no MW analogues (Huxor et al. 2004); whether this implies they are a distinct population or a continuation of the log-normal distribution of GC structural parameters requires a complete, magnitude-limited sample of GCs in these galaxies out to large radius.

III. The Pan-Andromeda Archaeological Survey (*PAndAS*)

We propose to obtain contiguous $g-$ and $i-$band imaging of the M31/M33 sub-group over a total area of over 300 sq. degrees, probing M31 to a projected radius of 150 kpc and M33 to a projected radius of 50 kpc, deep enough to detect giant stars in these galaxies more than 3 magnitudes below the tip of the RGB. The complete survey will provide the *first* contiguous, panoramic view of galaxy haloes over a volume of ~ 15 million kpc^3, complete to a surface brightness limit of $\sim 32 - 33\,\mathrm{mag\,arcsec}^{-2}$. The survey depth and the detail that will be revealed will be unreached and unrivaled by any other current or planned wide field survey (Figure S3). It will be a benchmark study of galaxy structure and will provide the primary dataset for comparison to galaxy formation models spanning an order of magnitude in halo mass. We stress that **this survey is only possible for the M31/M33 sub-group, and it is only possible using the unique capabilities of CFHT/MegaPrime**.

The **primary science goal of the Pan-Andromeda Archaeological Survey** *(PAndAS)* is to construct the deepest and most complete panorama of galaxy haloes available, to compare to and constrain cosmological models of structure and galaxy formation over an order of magnitude in halo mass. In particular, we will make the first derivation of the *global* shape and inhomogeneity of galaxy stellar haloes, and we will obtain a complete census of, and statistical quantification for, all structures and substructures in the outer regions of M31 and M33. *Structure formation* is predicted to be scale-free, and the factor of ten variation in halo mass between M31 and M33 will give PAndAS significant discriminating power between different *galaxy formation* models which attempt to relate mass and light on galactic scales. Further, PAndAS will probe the interface region between M31 and M33, exploring evidence for current and past interactions between these galaxies, their satellites and their stellar haloes. Ibata et al. (2007) show that the stellar haloes of M31 and M33 overlap; a complete understanding of either galaxy is therefore unattainable without a complete characterisation of the other.

As we now explain, the legacy value of PAndAS - for M31, M33, the Local Group, dwarf galaxies, globular clusters, stellar populations, galaxy formation and MW structure - is immense. It will become the primary reference dataset for all subsequent studies of the stellar populations of these galaxies, and will remain so into the era of Thirty Meter Telescopes and beyond.

An unprecedented view of galaxy structure

The most significant uncertainties in ΛCDM-motivated models of galaxy formation relate to the connection between baryonic and dark matter structures, since the evolution of baryons is followed through empirical, semi-analytic prescriptions which lack a well founded, physical basis. A necessary pre-requisite for improving these models is a census of the luminous content of galaxy haloes over a range of mass to extremely low surface brightness; this can best be achieved for the M31/M33 sub-system (Figure S1).

Historically, there are two competing ideas for galaxy halo assembly, both of which are now believed to contribute in the CDM hierarchy. The first originates in Eggen, Lynden-Bell, & Sandage (1962), where the stellar halo forms early and quickly during the initial collapse of the galaxy. Recent simulations by Abadi et al. (2006) suggest that the halo consists of those stars formed during the early merging of proto-galactic fragments in the initial galaxy collapse. The second process which is believed to contribute stars to the halo has its origin in Searle & Zinn (1978), where CDM satellites which pass close to the center of the galaxy are tidally disrupted, depositing their stars in the halo (Bullock & Johnston 2005). This latter process is more gradual and occurs over a much longer timescale. These models make different predictions regarding the density profile and shape of the stellar halo, its age and age spread, and its metallicity distribution. The first predicts a more concentrated, homogeneous halo, both in terms of age and spatial distribution, whereas the second will produce more streams and substructure, an inhomogeneous metallicity and age distribution, and a more extended stellar halo. PAndAS will measure these key observables and determine the relative importance of these two modes of halo formation.

The macro-scopic structure of the stellar halo of $L_\star$ galaxies additionally depends critically on the detailed physics of star formation in dark matter sub-haloes. Reionization and stellar feedback can suppress star formation in lower mass sub-haloes (Bullock et al. 2000; Kravtsov et al. 2004) leaving the most massive sub-haloes as the source of halo stars. Larger sub-haloes are only tidally disrupted deep within the potential well so one expects a more concentrated density profile of halo stars characterized by a steeper power-law index and smaller scale radius. Furthermore, the total number of stars in the stellar halo is an indicator of the star formation efficiency in sub-haloes. The baryons within the predicted hundreds of dark matter sub-haloes are presumably a significant source of halo stars, and so a count of halo stars will measure the star formation efficiency and its dependence on sub-halo mass.

Tracing galaxy assembly with proto-galactic building blocks

PAndAS will discover effectively all tidal streams in the haloes of M31 and M33 down to very low surface brightness, including probing the halo of M31 away from the area dominated by the giant stellar stream. Subsequent spectroscopic follow-up with Gemini/GMOS and Keck/DEIMOS will allow for a kinematic decomposition of the halo substructures and the accretion history of these galaxies to be inferred. Despite inevitable stochastic variation in accretion histories, galaxy formation models make well-defined predictions on this topic (e.g., Bullock & Johnston 2005; Abadi et al. 2006; Diemand et al. 2007). For example, the majority of the stars in the halo are contributed by the $\sim 10-20$ most massive accreted sub-haloes (similar perhaps to the progenitor of the giant stream). More than half the stellar mass of the halo is in place 8 Gyrs ago, and effectively all of the halo is in place 4 Gyrs ago. Stellar haloes beyond ~ 50 kpc are dominated by late accretions, although very few late accretions of massive satellites are expected. Our new inventory of all stellar substructures in M31 and M33 will open up the opportunity to explore their accretion histories and test these fundamental predictions.

The prevalence of substructure is a key observable to compare to hierarchical formation models. Ibata et al. (2007) suggest that the outer halo of M31 is very inhomogeneous and under-abundant in predicted ΛCDM satellites. However, without more complete halo coverage we cannot determine if results from the south-east quadrant reflect the global average for M31. Further, PAndAS will allow for a robust *statistical* quantification of substructure properties in M31 and M33: what is the power-spectrum of stellar density fluctuations? What is the luminosity function, metallicity distribution and surface brightnesses of these fluctuations? PAndAS will not only discover substructures, but will also measure their broad star formation histories and luminous properties.

The dwarf galaxy – dark matter connection

Dwarf galaxies occupy unique roles as the objects most likely to have formed first and as the most dark matter dominated systems in existence. A famous prediction of CDM is that M31-size galaxies should be surrounded by hundreds of dark matter satellites, but only a few tens of dwarf galaxies are observed. Recently, many ultra-faint dwarf galaxies have been discovered in the MW halo, although the numbers still fall short of CDM predictions by a factor of ~ 10 (Belokurov et al. 2007). M31/M33 is the only other sub-group in which comparably faint dwarf galaxies can be observed, and there have been many recent discoveries (Zucker et al. 2004, 2007; Martin et al. 2006; Majewski et al. 2007; Ibata et al. 2007).

To reconcile current observations with CDM predictions, it has been suggested that not all dark matter haloes contain stars (Bullock et al. 2000; Kravtsov et al. 2004). A statistical quantification of dwarf galaxy properties - particularly luminosity and mass functions - are strong tests of galaxy formation models which suppress star formation in low mass haloes. The radial profile of the dwarf galaxy distribution in comparison to other halo tracers, such as individual stars and GCs, is also a key test of formation scenarios (e.g., Moore et al. 1999). It is therefore vital to obtain complete inventories of dwarf galaxies around the MW, M31 and M33 for a robust test of these fundamental predictions. Extrapolation of our current discovery rate suggests that the M31 satellite population *may be incomplete by more than a factor of two*, with at least 15 dwarfs awaiting discovery to a magnitude limit of $M_V \sim -7$ (Figure S2).

Dwarf galaxies are among the least-massive stellar systems and so are excellent probes of their environment; for example, dwarf satellites can be used to measure the mass of their host galaxy (Evans & Wilkinson 2000). The M31 satellite system, however, has a gross assymetry in its spatial distribution, suggesting that previous surveys have introduced a large dynamical bias into the known population (McConnachie & Irwin 2006b). Comparison of the MW and M31 dwarf galaxies can help reveal the role of environment and tides in determining dwarf properties (McConnachie & Irwin 2006a), and has already suggested the existence of fundamental differences between the MW and M31 dark matter sub-halo populations (Peñarrubia et al. 2007). Indeed, internal dynamics of dwarf galaxies provide some of the strongest constraints available on the fundamental properties of the dark matter particle (e.g., Strigari et al. 2007). The discovery and analysis of dwarf galaxies around M31 and M33 is therefore important both in terms of understanding the dwarfs, and in terms of understanding their hosts.

Globular clusters: tracers of galaxy evolution

In the MW, GCs are found out to 120 kpc galacto-centric distance and have traditionally been the linchpin defining the true extent of the halo. The outer-halo objects – the Palomar-type clusters and the ultra-faint dwarfs – overlap in the $M_v - r_h$ parameter space (Belokurov et al. 2007), challenging our definitions of what constitutes a GC or a dwarf galaxy. In addition, M33 is host to a large population of intermediate-age GCs that do not have any known counterparts in the MW or M31 (e.g., Sarajedini et al. 1998; Chandar et al. 2002); interpreting GCs as relics of epochs of very active star formation indicates that the evolution of M33 at $z \sim 0.5$ was very eventful and perhaps significantly different from either of its two more massive counterparts.

GCs at large galacto-centric radii were presumably among the last systems to be accreted by their host, and determining their age and relative properties is fundamental to understanding the formation of the outer haloes of galaxies (e.g. Mackey & van den Bergh 2005). The fact that the globular cluster mass function (GCMF) is largely independent of galacto-centric distance has long been thought to indicate that its near-universal shape and turnover mass are mostly built in at birth. Recent models (e.g., McLaughlin & Fall 2007; Jordán et al. 2005) argue that dynamical evaporation coupled with a variation of mean cluster density can robustly produce the same effect. M31 has a three times richer GC system than the MW and must have corresponding numbers of outer-halo objects. Those found so far by our survey (Huxor et al. 2004, 2008) already stretch the parameter space of GCs further. We will measure the structural parameters for a spatially-complete, magnitude-limited census of GCs in M31 and M33 to large galacto-centric radius to obtain a larger GC database than is possible for the MW to test models of the origin and evolution of the classic log-normal GCMF.

A deep study of the Milky Way

PAndAS will also probe over $300\,$sq. degrees of the stellar halo of the MW. Several large-scale, MW stellar substructures are expected to be found in our line of sight to M31 and M33 (Martin et al. 2007); mapping their extent and obtaining spectroscopic follow-up will allow for the accretion history of the MW halo to be probed with this dataset. Comparison of star-counts and colour-magnitude diagrams to models of the structure of the MW halo (e.g., Robin et al. 2003) along different sight lines through the halo will discriminate between models and allow for an estimate of halo shape. This is particularly effective when used in conjunction with other MW survey areas, such as the Virgo Cluster CFHT Large Program (P.I. Ferrarese), which probes the halo of the MW on the opposite side of the sky to PAndAS.

IV. Summary

We have demonstrated our ability to use CFHT/MegaPrime to obtain world-class results. We now ask to obtain a panoramic census of M31 to a radius of $150\,$kpc, and M33 to a radius of $50\,$kpc, covering their haloes over a volume of some $15\,$million kpc^3 and complete to a surface brightness limit of $32 - 33\,$mags arcsec^{-2}. This survey takes full advantage of the unique niche occupied by CFHT/MegaPrime, in its ability to survey a large area in a reasonable amount of time to a level which resolves individual stars in the halo of M31/M33. Gemini/GMOS and Keck/DEIMOS can provide access to the stellar kinematics and chemistry, and Subaru/SuprimeCam and HST/WFPC2/ACS/WFC3 can obtain deep photometry to derive detailed star formation histories. Next-generation spectrographs, such as the proposed Gemini/WFMOS, will potentially allow for a complete dynamical de-convolution of the structure of, and substructures in, M31 and M33. However, only CFHT/MegaPrime can conduct the discovery observations to produce a census of their structure and substructure to low surface brightness, and which will allow for their global physical properties to be determined.

The **Pan-Andromeda Archaeological Survey** (*PAndAS*) will be unprecedented and unrivaled by any current or foreseeable survey. Its legacy for M31, M33, the Local Group, dwarf galaxies, globular clusters, stellar populations, galaxy formation and MW structure will be significant; it will become the benchmark for comparison to cosmological models of galaxy formation which relate the dark matter mass distribution to the observable baryonic structure of galaxies. PAndAS will cover ~ 320 sq. degrees of the M31/M33 sub-group; including our extant CFHT/MegaPrime coverage, we require 226 hrs of dark time to complete this survey. It can only be achieved for the M31/M33 sub-group, and it can only be achieved using the unique capabilities of CFHT/MegaPrime.

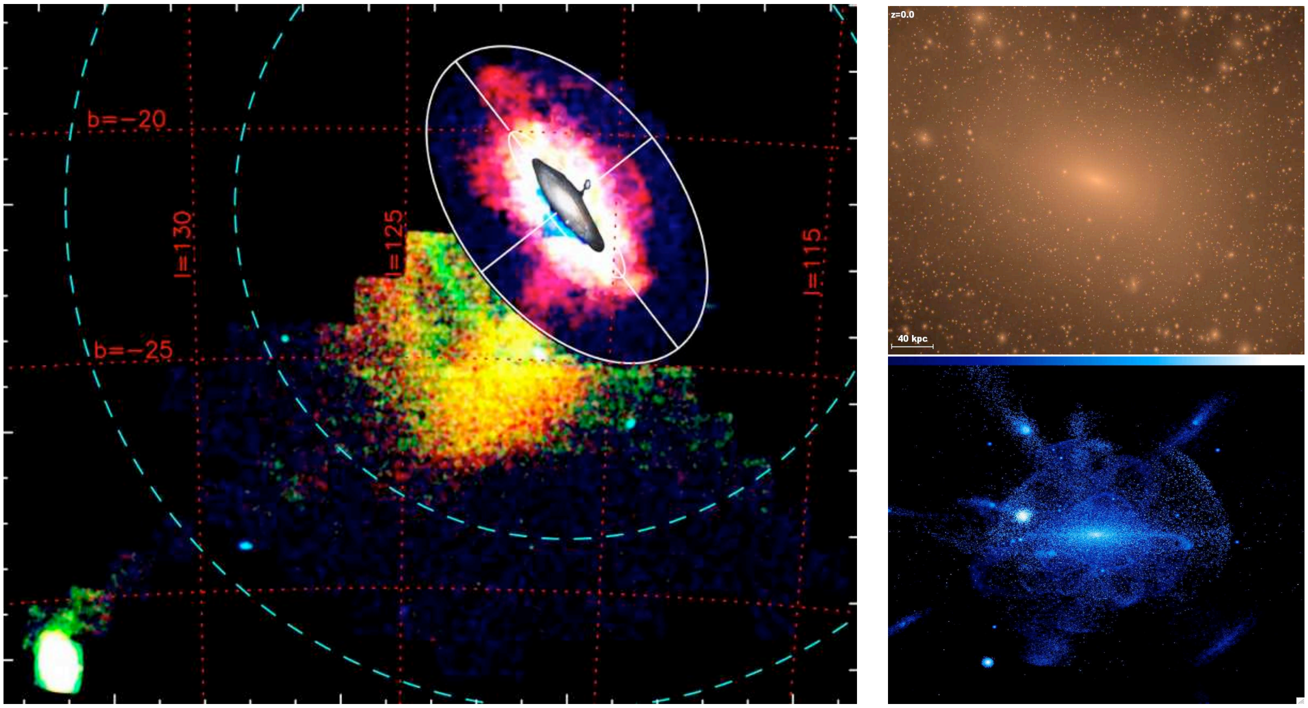

Figure S1: Left panel: The CFHT/MegaPrime survey of the south-east quadrant of M31 (Martin et al. 2006; Ibata et al. 2007). Giant stars in M31 are colour-coded according to their locus on a colour-magnitude diagram. Numerous complex, low-surface brightness, structures are observed. Top right panel: the predicted distribution of *dark matter* substructure in a galaxy halo from the *Via Lactea* simulation (Diemand et al. 2007). Bottom right panel: the predicted distribution of *stellar* substructure in a galaxy halo from Bullock & Johnston (2005). Detailed, panoramic, observations of galaxy structure and substructure are required in order to test these models and determine the relation between mass and light on galactic scales.

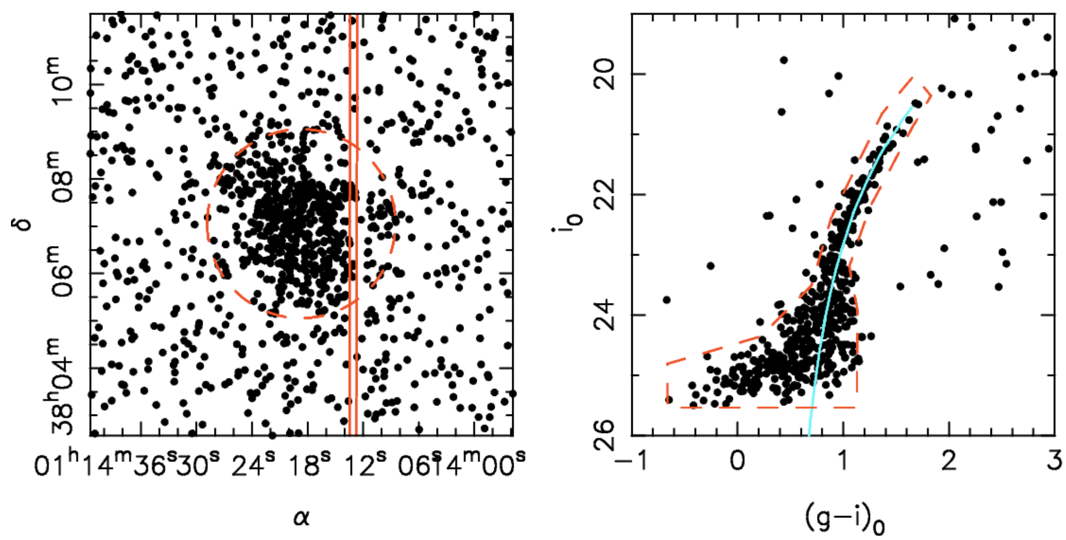

Figure S2: The discovery of Andromeda XV, one of five new dwarf galaxies so far found in our CFHT/MegaPrime survey of M31. Left panel: Spatial distribution of stars in a 12×12 arcmin area of the survey. Vertical red lines mark chip boundaries. Right panel: colour-magnitude diagram of stars within the dashed circle in the left panel. A RGB (with isochrone overlaid) and horizontal branch are observed, indicative of a dwarf galaxy with a predominantly old stellar population. PAndAS will discover effectively all such dwarf galaxies and globular clusters around M31 and M33.

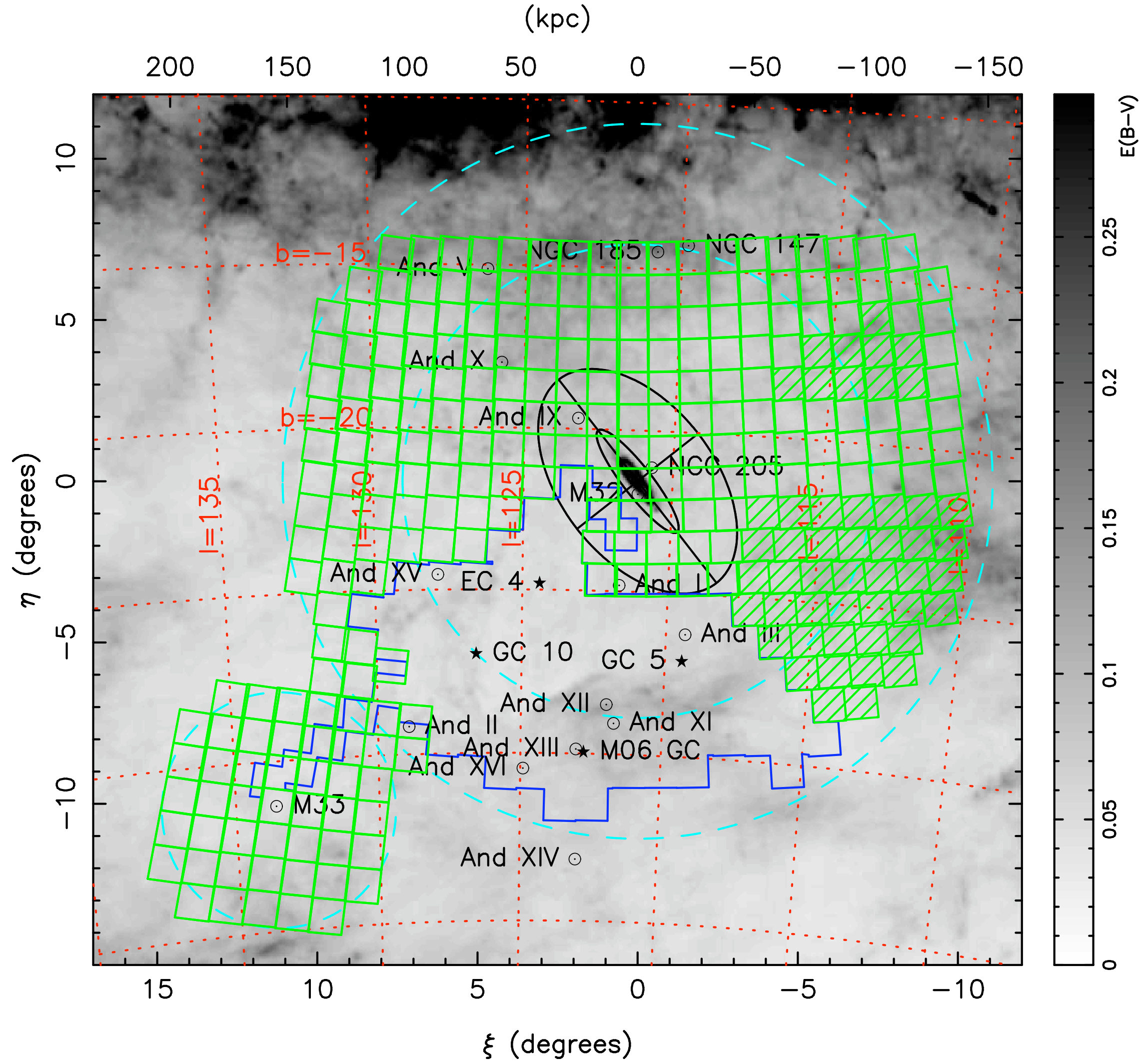

Figure S3: The Pan-Andromeda Archaeological Survey (PAndAS). Each tile represents a CFHT/MegaPrime field. The blue line de-limits the survey region obtained previously from the French TAC (P.I. Ibata). The hatched green tiles in the south-west quadrant correspond to the area surveyed through the Canadian TAC by the end of S07B (P.I. McConnachie). Open green tiles correspond to the requested area new in this proposal. The centers of M31 and M33 are marked with circles. The inner ellipse represents a disk of inclination 77 degrees and radius 2 degrees (27 kpc), the approximate edge of the regular M31 HI disk. The outer ellipse shows a 55 kpc radius ellipse flattened to $c/a = 0.6$, the limit of the original INT/WFC survey. Major and minor axes of M31 are indicated. The inner and outer dashed circles centered on M31 correspond to projected radii of 100 kpc and 150 kpc, respectively. The dashed circle centered on M33 corresponds to a projected radius of 50 kpc. The grey scale shows Galactic extinction measured by Schlegel et al. (1998). The Galactic foreground increases northward toward the Galactic plane. M31 satellites and discoveries from our extant CFHT/MegaPrime survey are highlighted.

Abadi, M. G., et al. 2006, MNRAS, 365, 747
Belokurov, V., et al. 2007, ApJ, 654, 897
Bullock, J. & Johnston, K. 2005, ApJ, 635, 931
Bullock, J., et al. 2000, ApJ, 539, 517
Chandar, R., et al. 2002, ApJ, 564, 712
Chapman, S., et al. 2006, ApJ, 653, 255
Chapman, S. et al. 2007, ApJ, 662, L79
Diemand, J., et al. 2007, ApJ, 667, 859
Eggen, O. et al. 1962, ApJ, 136, 748
Evans, N., Wilkinson, M. 2000, MNRAS, 316, 929
Fardal, M., et al. 2007, MNRAS, 380, 15
Ferguson, A., et al. 2002, AJ, 124, 1452
Gilbert, K., et al. 2006, ApJ, 652, 1188
Huxor, A. P., et al. 2008, ArXiv:0801.0002
Huxor, A. P., et al. 2004, astro-ph/0412223
Ibata, R., et al. 2004, MNRAS, 351, 117
Ibata, R., et al. 2001, Nature, 412, 49
Ibata, R., et al. 2007, ApJ, 671, 1591
Irwin, M., et al. 2004, SPIE, Vol 5493, p411
Irwin, M., et al. 2005, ApJ, 628, L105
Johnston, K. V., et al. 1996, ApJ, 465, 278
Jordán, A., et al. 2005, ApJ, 634, 1002
Klypin, A., et al. 1999, ApJ, 522, 82
Kravtsov, A. V., et al. 2004, ApJ, 609, 482
Mackey, A., vdBergh, S. 2005, MNRAS, 360, 631
Majewski, S. et al. 2007, ApJ, 670, L9
Martin, N. F., et al. 2007, ApJ, 668, L123
Martin, N. F., et al. 2006, MNRAS, 371, 1983
Mayer, L., et al. 2006, MNRAS, 369, 1021
McConnachie & Irwin 2006, MNRAS, 365, 902
McConnachie, et al. 2003, MNRAS, 343, 1335
McConnachie, et al. 2004, MNRAS, 351, L94
McLaughlin, D. & Fall, S. 2007, A:0704.0080
Moore, B., et al. 1999, MNRAS, 310, 1147
Navarro, J. F., et al. 1995, MNRAS, 275, 720
—. 1996, ApJ, 462, 563
—. 1997, ApJ, 490, 493
Norberg, P., et al. 2001, MNRAS, 328, 64
Peñarrubia, J., et al. 2007, ApJ, 672, 904
Robin, A. C., et al. 2003, A&A, 409, 523
Sarajedini, A., et al. 1998, ApJ, 508, L37
Schlegel, D., et al. 1998, ApJ, 500, 525
Searle, L. & Zinn, R. 1978, ApJ, 225, 357
Spergel, D. N., et al. 2007, ApJS, 170, 377
Strigari, L., et al. 2007, Ph.R.D., 75, 083526
Zucker, D., et al. 2004, ApJ, 612, L121
Zucker, D., et al. 2007, ApJ, 659, L21

Technical Justification

We propose to use **the same successful strategy as our extant CFHT/MegaPrime surveys:**

Survey depth and exposure times

With its high sensitivity and immense field of view, CFHT/MegaPrime is by far the best instrument for this project. The stellar density in the outer halo of M31 is much lower than the inner halo regions we previously surveyed with the INT/WFC, and it is necessary to probe deeper down the RGB (to $g \sim 25.7, S/N = 10$) to obtain sufficient statistics to identify structure and probe the global stellar populations. From our previous experience with CFHT/MegaPrime, we typically expect ~ 300 stars per sq. degree in the M31 halo at the survey limit of 150 kpc, although substructures/voids will enhance/degrade this signal. (Figures 18 and 19 in Ibata et al. (2007) demonstrate that a pseudo-INT/WFC survey of the outer halo at shallower depth does not reveal the majority of the substructure which we otherwise observe using the detection limits requested here; the higher S/N at $g > 25.5$ is essential for outer halo studies.) From previous experience with CFHT/MegaPrime, in dark time, and good (0.7 arcsec) seeing, we can reach $g = 25.7$, $i = 24.5$ ($S/N = 10$) with 1350s exposures each in g and i, split into 3 dithered sub-exposures to remove cosmic rays. With calibration fields (below) and overheads, this amounts to 3400 s per field.

Choice of survey area

M31 and M33 are the best and most accessible targets for an extra-galactic, panoramic, study of stellar haloes to $\sim 33\,\mathrm{mags\,arcsec}^{-2}$. This limit is set by the depth we can probe down the luminosity function to identify stellar populations with statistical significance (in sparse areas, we need to reach fainter stars to identify stellar populations with the same significance). The requested exposures probe M31 and M33 to 150 kpc and 50 kpc, respectively, at which point the surface brightness of the haloes drops below $\sim 33\,\mathrm{mags\,arcsec}^{-2}$ (Figures 42 and 48 of Ibata et al. 2007). The inhomogeneous/stochastic nature of stellar haloes/galaxy formation requires that as close to 100 % of the accessible stellar halo is probed as possible. The survey area in Figure S3 is designed to do just this: PAndAS will survey 100 % of M33's halo to 50 kpc, 100 % of M31's halo to 100 kpc, and 77% of M31's halo between 100 – 150 kpc ($\sim 90\%$ of M31's halo to 150 kpc). We have decided not to survey the entirety of M31's halo at very large radius in the north, given the large area we already require and the demand on CFHT time allocation. Since the influence of the Galactic plane in this region is the largest, it is the obvious area to forego. If significant M31 structures are found to extend into this region from our proposed survey area, we will submit GO proposals to obtain supplementary data as required.

Astrometry and Photometry

Astrometric calibration will be via the numerous unsaturated 2MASS point sources available per field. For CFHT/MegaPrime, we use a standard ZPN projection with a radially symmetric correction,

$$r_{true} = k_1 \times r + k_3 \times r^3 + k_5 \times r^5 + ... \qquad (1)$$

where r_{true} is an idealized angular distance from the optical axis, r is the measured distance, and k_1 is the scale at the center of the field. Coupled with a linear "plate" constant solution for each detector

$$\xi = a * x + b * y + c \qquad \eta = d * x + e * y + f \qquad (2)$$

we find that this gives average astrometric residuals over the whole field of order 100mas. The global systematics in 2MASS (on the ICRS system) are also below the 100mas level.

Elixer provides first pass external photometric calibration. As with our existing M31 survey, we will take two short exposures per field in photometric conditions (45s in g and i), with field centers offset by half a degree on both axes. These fields are essential for reliable dataset calibration; the overlaps with the science fields are used to define an overall system calibration accurate at the $1 - 2\%$ level.

Contamination I. Background galaxies

Compact elliptical galaxies at $z \sim 0.5$ are a significant source of contamination. We remove these by classifying detected sources using an algorithm developed for the INT/WFC survey (*Data Management*). We have performed simulations degrading the HDF to simulate a 1350s CFHT/MegaPrime exposure with 0.7 arcsec seeing and find that we misclassify ~ 2000 galaxies per sq. degree as stars. This number triples in 0.9 arcsec seeing. Since our ability to detect structures in the halo of M31 is limited by this contamination, we request good seeing (≤ 0.8 arcsecs) to perform accurate star/galaxy classification. Colour separation will reduce the contamination rate further (Figure T1). Of course, the detection limit will depend upon the size of the substructure, but for instance, a 1 sq. degree (~ 14 kpc) structure with ~ 1000 RGB stars (corresponding to a mass of $\sim 2 \times 10^5\,M_\odot$ for a normal stellar population) could be detected at a confidence level of $\sim 20\sigma$ in 0.7 arcsec seeing. (This detection estimate assumes a uniform background galaxy distribution; for ellipticals at $z \sim 0.5$, one degree corresponds to ~ 25 Mpc, so assuming homogeneity is reasonable.) Note also that we can use barely resolved galaxies, which should have a similar distribution to the unresolved galaxies, to identify any regions where the background large scale structure degrades the signal due to halo substructure.

Contamination II. Galactic foreground

As we have successfully demonstrated in Ibata et al. (2007), Galactic foreground dwarf contamination can be accounted for using the Besançon Galactic model. This model works exceedingly well, predicting the star-counts correctly to $\sim 2\%$, and can be further refined by normalizing the counts to "clean" areas of the colour-magnitude diagram which are absent of M31 stars. Galactic contamination is therefore not a concern in the southern half of the survey, where we have already demonstrated feasibility. In the northern hemisphere, which extends closer towards the Galactic plane, the contamination will be significantly larger. However, by restricting analysis to a colour interval ($0.8 < g - i < 1.8$) that is relatively free of Galactic stars (Figure T1), the contamination can be greatly reduced. Using the Besançon model to create a synthetic realization of the foreground populations as a function of colour, we find that the contamination that we will incur in the $0.8 < g - i < 1.8$ interval is at most, a factor of 2.5 worse than in the regions surveyed previously. This simply means that we will have to increase slightly our spatial boxes at the very northern end of the survey to achieve the same statistical detection level as in the southern region. Further, we note that we have chosen to limit our analysis to fields with $b \lesssim -14$ degrees to make the most efficient use of CFHT. Thus, galactic contamination is not problematic for this survey. Follow-up spectroscopic work will make use of additional spectral diagnostics for dwarf – giant separation of *individual* stars (Chapman et al. 2006; Gilbert et al. 2006).

Foreground extinction is shown in Figure S3 from Schlegel et al. (1998). It is generally small, but reaches $E(B-V) \simeq 0.15$ for some northerly fields. This level of extinction is not a problem for this science, and can be corrected for by cross-correlating the extinction maps with our detected sources.

Scheduling and Time-line for Scientific Deliverables

Table T1: Proposed time-line for data-acquisition and primary science deliverables enabled by observations

Time	Data Acquired	Survey Milestones	Main Science Deliverables Enabled
S08B	SW quadrant	M31 S halo to 150 kpc	DG, GC discovery/individual object analysis
	M33 area	M33 halo to 50 kpc	Full M33 analysis
S09B	N halo (100 kpc)	M31 halo to 100 kpc	Statistics of substructure
S10B	N halo (150 kpc)	Complete survey	Global structure/model comparison
End of 2011			

226 hours of dark time (with overheads and calibration fields) are required for the 238 fields which will complete PAndAS (Figure S3). Our favoured, but not required, option is to split time equally between the three 'B' semesters [S08B-S10B]: Table T1 shows this sub-division, and the time-line it enables. **The science return of PAndAS is immediate**: *by the end of S08B,* $>50\%$ *of M31's halo to 150 kpc and M33's entire halo to 50 kpc will be observed. By the end of S09B, M31's entire halo to*

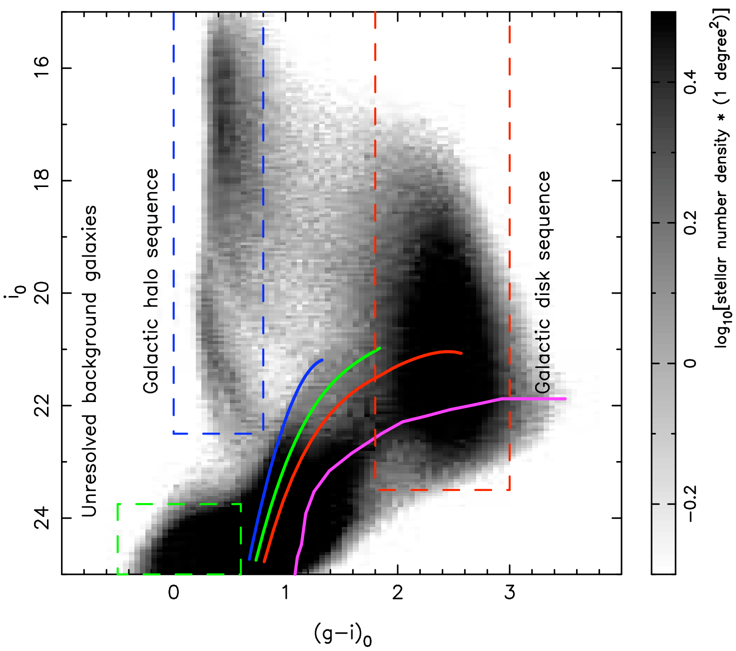

Figure T1: Colour-magnitude (Hess) diagram showing *all* sources classed as stellar in the south-east quadrant of M31's halo. Globular cluster fiducial sequences, shifted to the distance of M31/M33, are overlaid, and represent the locus of red giant branch stars in the stellar halo of M31. The locus of MW foreground stars (disk and halo) are marked. Note the reasonable colour separation between M31 giants and foreground dwarfs. Also marked is the locus of unresolved background galaxies which can be mistaken for stellar (point) sources at low S/N. These tend to bluer colours than the M31 giants, although the sequences overlap. Good seeing ($IQ \leq 0.8$ arcsecs) is required to minimise this source of contamination.

100 kpc will have been surveyed. The complete M33 analysis will commence immediately and the M31 analysis will begin with significant coverage and reasonable statistics. Reaching these unprecedented milestones early ensures (i) all team members are immediately involved in scientific analysis, (ii) efficient dissemination of results/publications, (iii) the rapid initiation of follow-up projects.

Synergy with other surveys

Surveys such as SDSS (SDSS II) and 2MASS have had considerable success in charting the outer regions of the MW to reveal how accretion events have contributed to its formation. M31 and M33 are the only other large galaxies in the Universe for which we can readily reach comparably faint surface brightnesses, and we trade a modest reduction in S/N compared to the MW for obtaining global perspectives for M31 and M33. It is vital that we capitalize upon the unique and complimentary insights into galaxy formation and structure afforded by these three galaxies.

A Pan-STARRS survey of the inner 7 degrees of M31 designed for microlensing studies lacks the coverage required for galaxy structure science. Pan-STARRS "$3\,\pi$", covering the entire northern hemisphere, will visit the sky 4 times a year for 3 years and reach the final depths given in Table T2. Five filter information is not necessary to identify faint halo structures. $3\,\pi$ will be 1 mag shallower in g and i than PAndAS. As previously discussed, this is insufficient to detect the majority of faint structures in M31 and M33, where the stellar densities are very low. The inevitable inhomogeneity of conditions sampled over the 3 year baseline further weakens 3π's competitiveness with PAndAS for the exploration of M31/M33. PAndAS is the only planned extra-galactic wide field survey capable of robustly identifying and quantifying the low surface brightness features indicative of hierarchical galaxy formation.

Table T2: PAndAS vs Pan-STARRS "3π"

(Vega mags)	g	r	i	z	y
Pan-STARRS $3\,\pi$ *(after 3 years)*	24.69	23.91	23.57	22.41	20.84
PAndAS	25.7	–	24.5	–	–

Follow-up and coordinated observations

Our collaboration have established programs with various instruments which will be used to follow-up results from PAndAS, particularly Keck/DEIMOS, Gemini/GMOS, VLT/Flames, UKIRT/WFCAM, CFHT/ WIRCAM, HST/WFPC2/ACS/WFC3, Subaru/SuprimeCam, *targeted* CFHT/MegaPrime pointings in different filters (u-band, narrow-band) and other multi-wavelength facilities. These observations will derive dynamical and chemical properties of the discoveries in PAndAS to advance our understanding of the cosmological context of M31, M33 and galaxy formation in general.

Observing Strategy

Right Ascension distribution of the observations (all semesters, B only)

Semester B	*226 hours total*
RA	Hours
00 - 04	212.7
04 - 08	
08 - 12	
12 - 16	
16 - 20	
20 - 24	13.3*

* All fields with $20 \leq$ RA ≤ 24 hrs (14/238) are at RA > 23 hrs 49 m.

M31 is best observed between August – November, when it is above an airmass of 1.5 for > 5 hrs per night from Mauna Kea (~ 3 hrs and ~ 1 hr in December and January, respectively). From the observing statistics given at
`http://www.cfht.hawaii.edu/instruments/imaging/MegaPrime/observingstats.html`,
suitable observing conditions for PAndAS ($IQ \leq 0.8$ arcsecs) occur $60-70\%$ of the time for i, $40-50\%$ of the time for g. With 12 nights of dark time per month, this gives roughly ~ 150 hrs every B semester for when this project can be conducted.

Data Management Plan

Data-analysis plan and quality assessment process

We have no real-time analysis requirements beyond the default quality assurance that takes place at the telescope and after running the Elixir pipeline. The Elixir pipeline will provide basic image processing, including first-pass photometric/astrometric calibration at the individual frame level. For all aspects of further data processing and management (e.g., image stacking, catalogue generation, morphological classification, and band-merging), we will use a variant of the VISTA Data Flow System (VDFS; Irwin et al. 2004). The optical pipeline processing component of the VDFS has been scientifically verified by successfully processing a range of wide field CCD mosaic imaging data, including our extant CFHT/MegaPrime surveys of M31. M. Irwin at the Cambridge Astronomy Survey Unit (CASU) will have primary responsibility for overseeing this additional pipeline processing and data calibration.

The processed data will be tagged with seeing measurements and other Data Quality Control (DQC) information. We will further check seeing, limiting magnitudes and sky background level for consistency with legacy data quality requirements. If necessary fields failing these checks at a significant level will be reinserted into the observing programme and noted for report to CFHT staff.

Data products

The data will be available to the participating communities immediately, and to the world one year later. All primary data products will be in the form of FITS files, either multi-extension image or binary tables for the catalogues. These will be compliant with VO standards to expedite publishing the results. The following additional data products will be created and made available: (i) Stacked and/or mosaiced data for dithered observations of single targets; (ii) Statistical confidence maps for all image products; (iii) Derived object catalogues based on a standard set of object descriptors including astrometric and photometric measures, and morphological classification; (iv) DQC database including measurements of seeing, average stellar shape, aperture corrections, sky background and noise levels, limiting magnitudes; (v) Homogeneous band-merged catalogues (gi from single pointings).

Description of available resources

Processing will make use of CASU facilities, currently comprising several high-end commodity PCs dedicated to optical data processing and access to multi-terabyte data storage volumes (capacity $\sim 100\,$TB). Data volume for PAndAS will be $< 0.5\,$TB. Overall long-term storage commitments of CASU are $\sim 1\,$PB, and so CASU can easily provide sufficient storage to meet survey requirements (i.e., storing both individual frames and stacked data products as required). Final data products will be made available in real-time to the collaboration using VO-access methods, with long term storage and world-wide access to data products delivered through CADC.

Team Membership and Responsibilities

Our collaboration has vast experience in *all* aspects of the required data reduction, observational analysis and theoretical modeling required to fully and successfully exploit PAndAS (Table D1). *We already have the required infrastructure established for PAndAS, we are familiar with the data we will obtain, and we have a demonstrated ability to use it to publish world-class results.*

Table D1: Primary responsibilities of team members, split into approximate science categories

Science Area	Principle Team Members
Data processing, reduction, products	Ibata, Irwin, McConnachie
MW foreground	Bienayme, Ibata, Irwin, Lewis, Martin, Seibert
Stellar populations	Davidge, Ferguson, McConnachie, Richer, Venn
Tidal stream	Chapman, Ibata, Irwin, Lewis, Penarrubia
Dwarf galaxies	Côté, Harris, Ibata, Irwin, Lewis, Martin, McConnachie
Globular clusters	Côté, Fahlmann, Ferguson, Harris, Puzia, Richer
Galaxy structure	Davidge, Ferguson, Ibata, McConnachie, Navarro
Dynamical models	Babul, Dubinski, Navarro, Peñarrubia, Widrow
Theoretical cosmology	Aubert, Babul, Lewis, Navarro