Australian Time Allocation Committee
Proposal for AAT Time

Semester: 2024B
Reference: A/2024B/1015
Submitted: No

Investigator	Affiliation	Observer	Student	PhD Thesis	Supervisor
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Grasha, Kathryn	Australian National University	Yes	No	No	
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Hopkins, Andrew	Australian Astronomical Observatory	No	No	No	
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Mai, Yifan	University of Sydney	Yes	No	No	
McDermid, Richard	Macquarie University	Maybe	No	No	
Mendel, Trevor	Australian National University	Maybe	No	No	
Owers, Matt	Macquarie University	Yes	No	No	
Pak, Mina	Macquarie University	Yes	No	No	
Quattropani, Gabriella	Macquarie	Yes	No	Yes	Owers
Rutherford, Tomas	University of Sydney	Yes	No	No	
Sweet, Sarah	The University of Queensland	Yes	No	No	
Taylor, Edward	Swinburne University of Technology	Maybe	No	No	
Tepper Garcia, Thor	The University of Sydney	Maybe	No	No	
van de Sande, Jesse	University of New South Wales	Yes	No	No	
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Zovaro, Henry	Australian National University	No	No	No	
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The Hector Galaxy Survey

The Hector Galaxy Survey aims to investigate the influence of environment on galaxy evolution with more precision than has ever been possible with previous or existing integral field spectroscopic (IFS) galaxy surveys. The uniqueness of the Hector Galaxy Survey lies in the combination of large integral field units, called 'hexabundles' giving resolved spectra across a larger field of view in each galaxy, and the highest spectral resolution of any large IFS instrument. This will enable us to determine the role of detailed large and small scale environment on how galaxies accrete material to form stars and build their angular momentum. We request 14 shared Hector nights for the Hector Galaxy Survey for 2024B.

	Dark	**Grey**	**Bright**
Total number of calendar nights requested this semester	**14**	**0**	**0**
Minimum useful allocation this semester	**7**	**7**	**0**
Additional nights required to complete project in future	**218**	**226**	**0**

Number of nights already awarded to this project: 0

Type of proposal (Open/Paid/Reserved): Open

Are these full nights: Yes

Remote Observing: No

Target of Opportunity: No

Long term status: No

Large program request: No

Preferred dates: **Earliest** 01 Aug 2024 **Latest** 31 Dec 2024

Impossible Dates:

Special scheduling constraints: January is not as useful because the targets will be observed at higher airmass than we would aim for.

Instrumentation

Instrument 1: Hector

Other requirements:

Related proposals (in this semester)

Telescope/satellite **Title of the proposal**

Previous related proposals

Reference	Title	Allocation	Percentage useful	Comments (Data ok? publications? etc.)
A/2022B/04	The Hector Galaxy Survey	8n	30	Commissioning - heavily cloud affected
R/2023A/01	The Hector Galaxy Survey	0	60	Good data taken
O/2023A/3002	The Hector Galaxy Survey	12n	60	Good data taken, reduced.
R/2023B/07	The Hector Galaxy Survey	0	58	Good data taken
O/2023B/3001	The Hector Galaxy Survey	14n	58	Good data taken, reduced.
R/2024A/03	The Hector Galaxy Survey	0	n/a	Not finished yet
A/2024A/06	The Hector Galaxy Survey	12n	n/a	Not finished yet.

0	n/a	Not happened yet

Description of the proposal for the general public

Where a galaxy grows up in the Universe can influence what it turns out to look like, and how it spins. Whether a galaxy is within large scale structures such as filaments or massive clusters, or on its own in voids can set how easily it can accrete stars and gas to grow in size and angular momentum. Using the new Hector instrument on the AAT, we working on what will be the largest '3-D' survey in the world, giving a spectrum at many points across each of 15,000 galaxies. The high resolution of the new Hector instrument and large field of view across the galaxies means we can measure not only the galaxy compositions but the rotations and dynamics in their gas and stars as well. This is crucial to understanding how galaxies grow.

1 The Hector Galaxy Survey Science Case

The ATAC Chair has granted an extra two pages for this proposal to outline the big picture of the full Hector Galaxy Survey (Hector-GS) as well as the focus of the 2024B semester.

1.1 The Hector Galaxy Survey Overview

What is the physical basis for the diversity of galaxy properties in the local Universe? This is the overarching question driving the Hector-GS. The answer lies in connecting the internal properties of galaxies to the detailed role of their environment. For the Milky Way, accretion from and interactions with satellite galaxies have shaped our galaxy. In extragalactic studies, there has been a paradigm shift from local and global density-based environment properties to defining environments based on both large-scale structure (filaments, walls, nodes) and where galaxies sit in velocity space. The unique capabilities of the Hector instrument will enable us to tackle this question with data that cannot be obtained with any other survey. The large survey size and spectral resolution, which is a factor of two better than any comparable instrument, will allow us to explore galaxy properties across the stellar mass function with exquisite environmental characterisation. The Hector-GS plans to observe 15,000 galaxies over 6 years, providing a groundbreaking data set that maximises the science productivity of the remaining life of the AAT.

The legacy of the Hector-GS will lie not only with the vast and rich data set that the survey will produce, but also in unique science that cannot be accomplished with any other instrument in the world. SAMI [12, 7, 14] and MaNGA [10] have been the largest IFS surveys to date. However, they lack a combination of the higher spectral resolution that allows stellar kinematics to be measured in a larger fraction and broader diversity of galaxies; the broad range in halo masses required to test the influence of the environment, including mapping the large cluster halos out to higher cluster radii; larger IFUs to get resolved spectra of galaxies to a larger galaxy radius; and a larger sample that will allow the key drivers of galaxy evolution to be statistically determined by sub-dividing the sample in physical parameter space with sufficient statistical accuracy.

The Hector-GS has optimised the science synergies with other large Australian projects. For example, the ASKAP WALLABY [21] and DINGO (https://dingo-survey.org/) surveys will combine their HI data with the Hector-GS to link gas accretion mechanisms and total gas masses from the inner galaxy to the scales probed by HI observations. A group of simulators are already active in the Hector science team, focused on a range of fundamental questions that can be addressed with the Hector-GS regarding the impact of large-scale structure on galaxy evolution. In addition, the Hector-GS regions have been selected to be within the ESO 4MOST WAVES North and South sky areas, which will provide exquisite environmental metrics to confirm the place of our galaxies within local and large-scale structures as well as their kinematic flows (https://wavesurvey.org/).

The Australian community selected the Hector instrument as the next dark-time instrument for the AAT. Membership of the Hector science team is open to all astronomers working in Australia - in some cases with contributions that are not telescope nights. The data will deliver a vast array of science opportunities to the already $\sim$ 70-strong Hector team, drawn from across the country from 8 Universities and the CSIRO as well as KASI in Korea.

Here, we request 14 nights from the common pool. The Hector Galaxy Survey science goals are built on a complete statistical sample of 15,000 galaxies, a number carefully set by predictions from simulations and experience with the SAMI data. Further justification of the survey size is given in section 1.3 below. To complete the full Hector survey on the planned 6-year timeframe requires 100 nights per year. We aim for a minimum of 90 nights per year and a target of 100. Due to the 13 lost Hector nights in 2024A, we aim for 63 nights in the next semester to stay on-track. **However, we are aware that this is an unusual semester and the telescope needs to remain active with productive programs in the dark and grey nights while 2dF is not available. We can confirm that if there are excess telescope nights after other awarded programs (e.g. KOALA) then the Hector Survey has sufficient targets to observe for more than 63 nights - as many dark and grey nights as available from August to December** (January is less productive for Hector due to higher airmass of targets). We have reserved 49 nights for Hector from four institutions this semester, so we require 14 more to reach our target. We seek these additional nights from the common pool, noting that some Hector institutions (UNSW, Monash) have chosen not to reserve Hector nights and instead contribute through the pool, while ANU has put enough nights into the pool to apply for further Hector nights.

1.2 Key Science Goals

(A) **How is the accretion of gas and angular momentum (spin) influenced by the local and global environment?** Cosmic structures over the mega-parsec scale, such as cosmic filaments and clusters where they intersect, strongly constrain the flows and thermodynamics of baryons in their vicinity. Simulations and theory predict that this impacts the accretion onto galaxies and, therefore, their spin, structure and, more generally, their dynamics. The world-leading Australian surveys WALLABY and WAVES (2024+) will map galaxies and their peculiar velocities in the local Universe with unprecedented detail. They will locate the Hector galaxies both in 3D space and dynamically within cosmic flows, permitting the most extensive analysis of correlations between large-scale structure morphology and Hector's galaxy-scale dynamics.

SAMI demonstrated the feasibility of such studies through the first detection of the alignment of galaxy spins with filaments [35], but the limited statistical power capped the significance of the results at $\approx 2\sigma$. It also precluded any analysis of cosmic walls, any multivariate analysis (field filaments, filaments in groups, filaments into clusters) and any detailed analysis of the corresponding kinematic disturbances in the outer parts of galaxies. [4] and [5] demonstrated the importance of spin filament alignments to understanding accretion of angular momentum in galaxies, and again found a larger sample over a wider mass range was required. With its increased sampling, wider field of view and wider coverage of clusters up to $2\,R_{\rm vir}$, the Hector-GS will allow for a deep analysis of how filament/wall, filament/group, and filament/cluster interactions impact galactic inflows, spin and structure. Such studies are very timely. Modern simulations predict, for instance, that cluster outskirts $(0.75 - 2\,R_{\rm vir})$ are regions of multiple transitions, strongly impacting the structure of galaxies. It is where satellite galaxies are expected to progressively align their orbit and spin to the central galactic plane, while aligned to the nearby cosmic filament at outer radii [34, 33]. While the orbit transition was detected in the SDSS [36], the spin counterpart requires the power of the Hector-GS.

(B) **Tracing the mass accretion and dynamical evolution of galaxies through utilising Hector's spectral resolution.** The SAMI Galaxy Survey was the first to clearly demonstrate the impact of the environment on the stellar-dynamical properties of galaxies. The largest dynamical changes are detected in the most massive galaxies ($\log(M_\star/M_\odot) > 11$) in the most extreme environments. Between $9.5 < \log(M_\star/M_\odot) < 11$, the dynamical transformation as a function of both mass and environment is significantly smaller [11, 13, 32]. In this regime, a factor of > 5 increase in sample size is paramount to understanding what physical processes determine a galaxy's morphology and dynamical structure. Nonetheless, the highest impact science is expected to come from the mass regimes currently out of reach of SAMI. Towards low stellar mass, there are hints that galaxies become more dispersion dominated [see also 15, 30, 2, 3], but this mass regime is currently below SAMI's spectral resolution. The higher spectral resolution of Hector will enable stellar kinematic measurements on a broader range of galaxies than any other survey. Similarly, for the most massive galaxies in extremely dense cluster environments, SAMI's current bundle size restricts measurements to the very core of these galaxies, while the vast majority of accreted material and transformation is predicted to take place at larger radii [$> 2R_e$; 29, 6, 28]. In both low and high-mass regimes, the Hector-GS will make breakthroughs.

Hector will also revolutionise our ability to measure high-order kinematic signatures that offer a complementary yet unique insight into the orbital structure of galaxies. Measurements from SAMI have resulted in well-cited results for high stellar mass galaxies [31], but the Hector-GS will probe the stellar kinematics of the low-stellar mass population in large numbers for the first time. Detailed Schwarzschild's orbit-superposition models [27] have now demonstrated that high-order kinematic signatures detect unique orbital substructures, and cosmological hydrodynamical simulations show that high-order signatures are the best probes for determining the amount of ex-situ versus in-situ material in galaxies [26]. The Hector-GS will yield an unprecedented number of galaxies ($N \sim 4000$) where high-order kinematics can be measured, across stellar mass, morphology, and environment, enabling detailed comparisons to simulations [e.g. 23, 26] that relate galaxy formation models to the stellar kinematics, to unravel the formation paths of galaxies as drivers of their present-day physical properties.

(C) **Directly identifying feeding and feedback in galaxies**. The Hector-GS will evaluate the balance of gas supply for star formation in all environments by imaging outflows from kinematic signatures and emission-line diagnostics of shocks and AGN. While a small number of galaxies in the SAMI survey had the right size and orientation to identify galactic winds and outflows [17, 18, 22], the larger IFU imaging fibre bundles, called 'hexabundles', and the Hector survey strategy will allow for the gas kinematics to be traced to higher effective radii within each galaxy. This, in turn, better captures the velocity structure, including the maximal rotational velocity, and the subtle signs of inflows, outflows and re-accretion at large radii for a much larger fraction of emission-line galaxies. Our modelling has shown that the higher spectral resolution in the blue will enable multi-component line fitting and distinguishing of AGN outflow signatures in the [OIII]500.7nm emission line, which is ambiguous with the lower resolution IFS surveys.

(D) **Testing the origin of gas and its influence on star formation in galaxies.** The kinematic misalignment of gas and stars is a key tracer of the origin of gas and the impact of gas accretion and mergers on star formation and the build-up of mass. It has been shown with SAMI [8] that the larger IFU size in Hector is needed to map the merger signatures and in-coming accretion from larger radii that is necessary to constrain galaxy formation models.

The broad interests of the Hector Science team met by this survey also include i) spatially resolving star formation rates, metallicities and stellar ages; ii) tracing galaxy star formation histories from stellar populations; iii) separating the formation histories and mechanisms for the disk and bulge components of galaxies and much more.

1.3 Survey Design and Target Selection

Sample Size Justification: The need for 15,000 galaxies has been carefully set by simulations of the highest impact Hector Science goal and based on experience with the SAMI data. A unique high-priority science goal for Hector is the correlation of the angular momentum of galaxies with their formation position within the large-scale structure. While the SAMI survey detected the first signature of galaxy spin alignments with cosmic filaments [35], the significance of the detection was limited to $\approx 2\sigma$ and precluded more detailed analysis. Based on predictions from simulations, it was remarkable that the faint spin-alignment signal at $z < 0.1$ was recovered above the 95% confidence interval, especially considering the relatively low number of galaxies (N=1418) in the sample [35]. However, as outlined in key science goal (A), the limited number of galaxies in SAMI makes it impossible to detect spin-alignment trends within galaxy sub-populations, nor does it allow for a detailed analysis of galaxies near cosmic walls, any multivariate analysis (field filaments, filaments in groups, filaments in clusters), or any detailed analysis of the corresponding kinematic disturbances in the outer parts of galaxies [4, 5].

We have determined that 15,000 galaxies observed over a wider area, such as the WAVES regions, will be essential to recovering the 3D alignments of galactic spins in all cosmic structures, particularly near filaments and walls. While SAMI and MaNGA combined already observed 13,000 galaxies, the environmental statistics are insufficient to carry out the proposed science goal (A) as the SDSS regions lack the required redshift completeness.

Furthermore, understanding the broader science goals in section 1.2, relies on sub-dividing the galaxy sample by stellar mass (4 bins from $10^{7.5}$ to 10^{12} $M_\odot$), morphology/colour (kinematic morphology - fast/slow rotators - and shape - elliptical, spiral, S0), local and global environment (position within local densities e.g. isolated galaxies, group members and radius of a galaxy within a cluster, and position within large-scale flows e.g. distance to filaments). The Hector Galaxy Survey aims for 180 galaxies per bin when subdividing into these 4 x 5 x 4 bins (requiring 15,000 galaxies) in stellar mass x environment x morphology/colour which will differentiate at the $\sim 15\%$ level between environmental influences on gas accretion and the resulting star formation and angular momentum build up in galaxies.

Survey Design: The Hector-GS field sample will probe a significant range in environmental densities, from the lowest density voids all the way to the centres of low mass clusters. However, the Hector-GS field sample volume does not contain rare massive

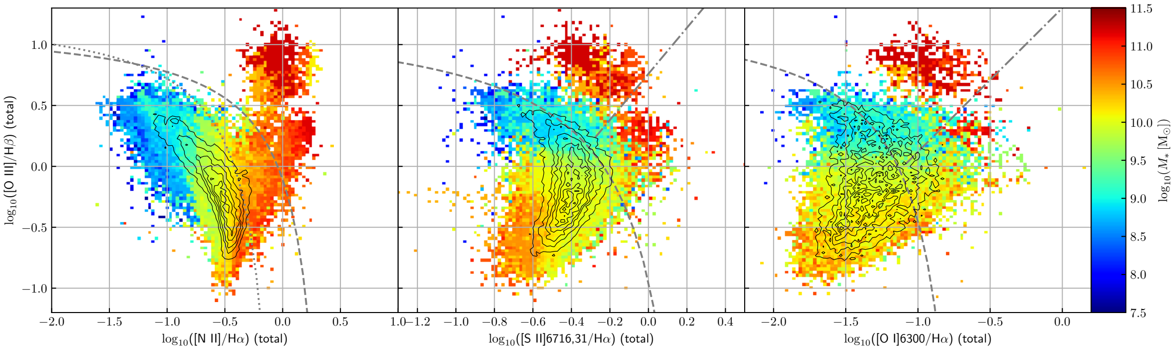

Figure 1: Optical diagnostic diagrams of individual spaxels from Hector galaxies, created using the spaxelsleuth python package. The colour of each cell represents the median host galaxy stellar mass of the spaxels in each cell, and the log-scaled contours represent the number density. The dashed, dotted and dash-dotted lines are the diagnostic lines from [19] and [20] which separate emission ratios indicative of star forming ionisation to the left of these lines and non-star-forming emission to the upper right of the lines. These show the effectiveness of Hector in measuring the ionisation and metallicity across galaxies, for a broad range in stellar mass and in a significant sample of low-mass galaxies, as indicated by the blue "wing" extending towards the left in each panel.

clusters ($M_{200} > 10^{14.5} M_{\odot}$). To sample the full range in environment density, the Hector-GS will observe an additional 11 galaxy clusters with $M_{200} > 10^{14.5} M_{\odot}$, which have existing high-quality optical *griz*-band imaging from the Dark Energy Survey [DES; 1]. Hector and SAMI are the only large IFS surveys to target rich cluster fields. Furthermore, the Hector-GS will go beyond the cluster science possible with SAMI by covering the cluster outskirts out to twice the virial radius. This will bridge the density regimes of field and cluster galaxies. These intermediate density regions are a crucial environment for the morphological transformation of galaxies. Thus, the Hector-GS will be the first IFS survey that truly covers the full range of environmental densities, to give the most comprehensive investigation of environment-driven galaxy transformation to date.

The field sample will be in two regions: one in the north galactic cap at $\delta \simeq 0^{\circ}$ (with known redshifts from SDSS, 2dFGRS and GAMA); and a second at $\delta \approx -30^{\circ}$ in the south galactic cap (with known redshifts from 2dFGRS). These are the "WAVES North" and "WAVES South" fields that will be observed with (unresolved) single-fibre spectroscopy using 4MOST as part of the upcoming WAVES survey from 2024. The alignment of the Hector Survey to these WAVES fields enables the environmental and large-scale structure information from WAVES, which is essential to the key science cases for the Hector Survey. Photometry for the target selection is based on deep optical KiDS imaging.

Target Selection: Target selection for the Hector-GS will follow a similar philosophy to that of the SAMI galaxy survey, using a selection function described by a series of steps in the redshift – stellar mass plane (see [7] for details). To avoid an overabundance of L_*-mass galaxies, we will sparsely select in the mass range $\sim 10^{10} - 10^{11}\,\mathrm{M}_{\odot}$. The final target selection selects 15,000 galaxies at $z \leq 0.1$.

The 2024B semester Hector observations will focus on two 60 sq. degree sub-regions in the WAVES South fields (H01 and H03) and the GAMA G23 field and 10 of the Hector-GS clusters. Enabled by the 2dF Hector Galaxy Redshift Survey, the clusters now also have sufficient redshift coverage for the selection of Hector targets in semester 2024B.

1.4 Hector performance so far

The Hector survey began in 2023. The first internal team data release in April 2024 with the fully-operational data reduction pipeline consisted of 3714 cubes (red and blue spectral ranges), featuring 1495 unique galaxies. There are further data that are awaiting reduction.

In previous proposals we featured data illustrating the science gains we are achieving due to the higher resolution, and the science-quality products now available which are contributing to the initial science cases below. We also showed early results for the highly unique science case of stellar kinematics in low-mass galaxies (see Section 1.2(B) above) plus we showed first results on the Hector cluster ram pressure stripping (early science program 3 - see Section 1.5(3) below).

Here we highlight two new results. Fig. 1 shows the quality of the Hector data for measuring ionisation of galaxies right down to the lowest stellar masses. These results rely on the effectiveness of the new multi-component emission line fitting code in which separation of line components is only now possible due to the high spectral resolution of Hector. Then the data products from SpaxelSleuth, are being used for classifying the ionisation in individual spaxels (e.g. star formation, AGN, plus gas metallicity).

Fig. 2 is a result from our early science program #3 (aligned to Section 1.2 A and C above) in which quenching of a galaxy due to the cluster environment is characterised in detail with Hector data.

1.5 Plan for Semester 2024B

The Hector instrument [9] has 19 hexabundles on galaxies in each field and two that image secondary standard stars for calibration. This semester, the Hector-GS aims to target 1580 galaxies in 63 dark/grey Hector nights (49 reserved nights on Hector, 14 shared-time nights requested here), with 2 fields per night and 19 galaxies per field (with weather overhead). Targets this semester are available from Aug-Jan (but Jan is not as useful due to higher airmasses of targets). To reach 15,000 galaxies, a future request of 100 nights per year over 5 years is required.

Targets for 2024B will be chosen from the main Hector survey input catalogue, but be specifically chosen to continue our key early science programs. They will particularly contribute to papers on the following 3 science cases:

Team Expertise

The Hector Science team has a wealth of experience with observing on the AAT, data reduction of integral field data, and with the instrumentation. This comes from a strong overlap with the SAMI science team members and senior team members who have used many instruments on the AAT. The observing process for Hector is similar to SAMI. 23 observers have been fully or partially trained so far for Hector, ensuring the team can provide two observers per Hector observing run.

Target List

Field Name	R.A. (deg)	Dec (deg)	r-band surface brightness/mag	Exposure time (min)	Instrument
H1	9 -- 21	-28.5 -- -33.5	22 / < 17.7	240	Hector
H3	39 -- 51	-28.5 -- -33.5	22 / < 17.7	240	Hector
G23	338 -- 352	-35 -- -30	22 / < 17.7	240	Hector
Abell 2399	329.3726	-7.7969	22 / < 17.7	240	Hector
Abell 151	17.1092	-15.4092	22 / < 17.7	240	Hector
Abell 119	14.0672	-1.25537	22 / < 17.7	240	Hector
Abell 85	10.4602	-9.3032	22 / < 17.7	240	Hector
Abell 3158	55.7704	-53.6531	22 / < 17.7	240	Hector
Abell 3266	67.7746	-61.4436	22 / < 17.7	240	Hector
Abell 3376	90.1529	-40.0326	22 / < 17.7	240	Hector
Abell 3391/3395	96.58/96.88	-53.69/-54.44	22 / < 17.7	240	Hector
Abell 3667	303.0917	-56.8152	22 / < 17.7	240	Hector
Abell 3716	312.8600	-52.7070	22 / < 17.7	240	Hector