Establishing the Galaxy Formation Rosetta Stone with Giant and Positionable IFUs

N. Drory (UT), N. MacDonald (UW), M. Bershady (UWisc), K. Bundy (IPMU), R. Yan (UK), D. Law (STSci), S. Allen (Stanford), A. Aragon-Salamanca (Nottingham), V. Avila-Reese (UNAM), F. Belfiore (Cambridge), D. Bizyaev (APO), M. Boquien (Antofagasta), M. Bureau (Oxford), N. Clerc (MPE), R. Croft (CMU), J. Dalcanton (UW), R. Davies (Oxford), A. Edge (Durham), E. Emsellem (ESO), A. Finoguenov (MPE), J. Holtzman (NMSU), A. Leroy (OSU), A. Merloni (MPE), A. Meza (U. Andrés Bello), A.J. Peterson (CMU), J. Rich (Carnegie), S.F. Sánchez (UNAM), M. Seibert (Carnegie), D. Thomas (Portsmouth), D. Wake (UW), K. Westfall (Portsmouth), A.M. Weijmans (St. Andrews), K. Zhang (UK),

We propose a transformative multi-tiered program that establishes the Rosetta Stone of galaxy formation by enabling 3D optical spectroscopy

- over 100s of square degrees in the Milky Way at 0.01 to 1 pc resolution;
- complete coverage of the LMC, SMC, M31 and M33 at 10-20 pc resolution; and
- observations of galaxies in the Local Volume out to Virgo distances while still resolving the critical GMC (~ 50pc) scale, which is not possible with the MaNGA sample (limited to ≥1 kpc spaxels).

This program enables physically critical scales in the MW and Local Group to be *resolved and connected to a representative cosmological volume* for the first time. Our key scientific goals are to resolve the sub-grid physics in these specific areas that underpin our physical models of galaxy evolution.

1. **Star-formation**: The local and global structure of star-forming regions is shaped by turbulence, instabilities, and the stellar winds and ionizing flux of embedded populations that must be resolved at scales of 10-30pc (the GMC scale). We will map the micro and macro processes that regulate the size and longevity of such regions starting with clouds in the MW and the local group, their interface to the diffuse ISM, and, using the observations of external galaxies, the emergence of kpc-scale patterns of star formation in the local volume.
2. **Star-formation histories**: We will establish a fundamental and comprehensive link between resolved color-magnitude diagrams and inferred star formation histories of unresolved stellar populations by bridging these two observational probes across a full range of galactic environments, metallicity, age, and chemical abundance.
3. **Ionization and feedback**: We will map radiation and feedback on scales ranging form 0.1-100 pc covering the the full range of single sources to the global ISM. We will uncover the ionization sources of the diffuse ISM, identifying shock networks where present, and linking probes of ionization with locally-coincident aging stellar populations.

To do this, the *Dynamic Ranger*™ instrument facility will be developed that maps all of the above processes across the full extent of all disk galaxies in the local group (including the Milky Way) and out to Virgo to provide a comprehensive picture of the local galactic macrocosm, and place it in the context of galaxy populations across cosmic time traced by existing and future surveys.

1. Grasping A-Omega with the Dynamic Ranger™ Instrument.

We will build a world-class competitive spectroscopic system for telescopes at APO and LCO based around a very large, flexible, lenslet-coupled (near 100% fill) IFU system of 5000 fibers using MaNGA IFU technologies and subsequent developments by the same team. A back-end array of replicated spectrographs capitalizes on the DESI design; each will cover 360-1000 nm at $R \sim 4000$ (FWHM) or 30 km/s (σ), resolving even low-dispersion structures in galaxies. A flexible input manifold will enable fiber feeds from a spate of telescopes including the APO 3.5, Sloan 2.5 m, du Pont 2.5 m, APO 1 m, LCO Swope, and ~ 6” Canon ultra-low scattering lens mounted to existing telescopes. All these feeds will be at the same f-ratio of ~ f/3.8 (using moderate focal reducers/expanders to form telecentric input beams), leading to a cascade of plate scales and single-IFU field sizes ranging from 2 to 50 arcmin diameter and spaxel sizes from 1.5 to 40 arcsec. This flexibility allows us to match FOV and plate scale to the dynamic range in size and distance of the objects of interest. Using abuttable ferrules, configurations with smaller IFUs will be independently positionable on the wide-field 2.5m-class telescopes to enable wider science application and to efficiently re-target regions of interest with higher spatial resolution in data gathered by the smaller telescopes (an adaptive sampling refinement technique).

2. From Orion to Virgo: Surveying the MW and nearby galaxies at 0.1-10s pc resolution

We propose a definitive study of diffuse (nebular) emission from ionized gas and stars from the Milky Way to look-back times of 5 Gyr.

2.1 Why this is needed: Observations on multiple physical scales are crucial to make the physical connections between the local and global properties of galaxies. Line ratios or equivalent widths do not add up linearly as the instrumental resolution changes as the constituents might be coming from physically distinct regions. In external galaxies, observations resolving individual clouds are still surprisingly rare. In the Milky Way, observations of individual gas clouds resolve their structure and kinematics in the radio, but global and resolved properties in other wavebands common to observations of external galaxies are lacking. Virtually no IFU observations of cloud complexes exist.

2.2 Why it has not been done before but can be done now: The reason is the lack of truly large IFU instruments. The proposed tiered system with *Dynamic Ranger*$_{\mathrm{TM}}$ allows us to survey the MW at low apparent spatial resolution covering 100s of square degrees using the smallest telescopes, and to perform pointed follow up observations of regions of interest with larger telescopes at higher resolution, using smaller IFUs positioned in the FOV of the wide-field larger telescopes for efficiency. The large IFUs allow us to fully cover the Local Group galaxies and objects to Virgo distances while still resolving the critical scale of GMCs.

For the first time, we will be able to cover complete cloud complexes in the MW, as well as the full Magellanic Clouds, M31, and M33 with optical spectroscopy. We propose a discovery mission, with coverage fraction of these objects increasing by factors >100 over extant observations, and a complete census of optical spectra in the Local Group. This dataset will allow us to understand in exquisite detail how spectra of distant galaxies are decomposed into stellar and gaseous components under a very wide range of physical conditions as well as allow progress in the study of individual clouds, star formation, local and global feedback, the diffuse ISM, HII regions, cloud and galaxy kinematics, and stellar populations. Our tiered system of spatial resolutions allows us to survey wide areas with coarse sampling, and subsequently use finer sampling on a larger telescope to zoom in on regions of interest. *In short, we will establish the Rosetta Stone of all galaxy surveys by tying the MW and physically critical resolved scales to a representative volume.*

2.3 Example program: Table 1 gives an example of what could be surveyed with 1000 visits at each level of our tiered hierarchy, assuming 1h average exposure times per visit; Table 2 gives estimated

Telescope	**Spaxel size** (arcsec)	**Field of View** (arcmin)	**Scale** (pc)				**Area per 1000 visits** (deg^2)
			MW	LMC/ SMC	M31/ M33	Virgo/ Fornax	
Canon lens	41	48	0.1-1	10			500
1 m (APO, Swope)	6	7	0.01-0.1		25		11
2.5 m (Sloan, du Pont)	2.5	3			10	100	2
3.5 m ARC	1.8	2				75	1

extended-source sensitivities. The details of a competitive and realistic science program within AS4 need to be studied in detail, and go much beyond the scope of this LOI. We are convinced, however, that our proposal holds much promise and think that a very compelling science case can be assembled as part of a next step in the AS4 process. We point out that our concept naturally scales by the choice of telescopes to include and the targets to cover. It can be scientifically very viable using a subset of the instruments and

Object	Area/ sq.deg	Spaxel (“)	V mag/ spaxel	S/N in 1 h per Å	Line flux (3σ)
Orion	2	48	13.7	33	1.3E-18
Rho-Oph	30	48	~ 16	10	1.4E-17
LMC	100	48	15.5	14	7.0E-18
SMC	17	48	15.4	15	6.1E-18
M31	7	6	20.2	5	5.6E-17
M33	100	6	19.8	6	3.9E-17

targets listed here. We’d like to develop that science case over the coming months, assuming support from the AS4 committee.

2.4 Technologies and Cost. As a base line we are considering the DESI spectrographs which can accommodate up to 750 x 107 µm OD fibers on each slit. Seven spectrographs will be deployed at each site to accommodate 5000 fibers. A connector and switching system would be implemented to change between IFU-MOS mode and the single on axis IFU, as well as switch between the feeds from each of the telescopes. By capitalizing on the DESI spectrograph design, IFU technology expertise developed within our team, and connector technologies developed by the APOGEE team we believe we can field an extraordinarily powerful survey instrument with low technical risk. The total cost for an array of 5000 fibers (7 spectrographs) including front ends is ~ $8M with the majority in hardware (see White Paper). The marginal cost for a single spectrograph is $1.05M, based on the DESI build. It is likely possible to reduce this cost in the future. It is expected that a large amount of the development labor will come from in-kind contributions.

3. Competitive Landscape.

On AS4 timescales, the Sloan 2.5m telescope with its current ~ 1000 single-fiber instrumentation will face competition from, e.g., MUSE, Subaru/PFS, MS-DESI, WEAVE and 4MOST, all single fiber and small FOV IFU systems. VIRUS is the only very large field IFU, but its low R ~ 700 and narrow 3600-5400 Å spectral range make it a special-purpose instrument. Very large IFUs are a new class of instruments made possible by replicated spectrograph technology. It is a niche not yet populated by a general survey-class instrument and project. We propose to overcome the problem of the very large dynamic range in object sizes as one moves from the MW through the Local Group to the local volume by feeding the same array of spectrographs (the vast majority of the investment) from a number of telescopes of varying diameter to achieve a high dynamic range of survey power. We note that while we have not included this in our current concept, adding *Dynamic Ranger*™ to Megallan and GMT telescopes continue the ~ doubling of plate scales presented in our current schema.

Other science applications: We invite other science teams to consider “killer apps” for the *Dynamic Ranger*™. One such program is the followup of intermediate-redshift clusters. A multi-IFU survey that takes advantage of the well-understood eROSITA selection (and X-ray imaging and spectral capabilities) of large and representative samples of clusters would provide critical insight into the complex astrophysical processes within the clusters, by revealing nuclear ICM cooling processes, star formation, AGN feedback and BCG formation in the densest region of our universe; all crucial, but not well understood, problems for structure formation today. Such a survey is astrophysically interesting in itself, and also necessary order to realize the promises of wide area clusters surveys as cosmological tools. In addition, by probing the central regions of those clusters with IFUs, one could take advantage of the gravitational lensing magnification to harness, in a systematic fashion, the power of these 'gravitational telescopes' in searching for the first galaxies and black holes.