AS4: *Unbiased Views of Young Stars in the Milky Way*

To: The After Sloan 4 Steering Committee c/o Juna Kollmeier, Chair

Dear Dr. Kollmeier, Dear Colleagues:

In 2015, a group of young and experienced specialists put together a white paper on an ambitious study of star formation in the Milky Way, based on a unique near-IR spectroscopic survey of young stars in a variety of galactic environments using the APOGEE facilities. Following the recommendations from the After-Sloan 4 (AS4) Steering Committee, we express here our intent to improve on out efforts to make a full proposal for an AS4 program.

Summary — Near–infrared spectroscopy within *SDSS*–V has the potential to revolutionize our understanding of the youngest stars and the groups and clusters they form. No current or planned mission is capable of characterizing large sets of these stars, which are typically obscured by their natal clouds (e.g., a problem for *Gaia*). A survey of about 2×10^4 young stars can turn the study of early stellar evolution into a precision science similar to the one describing main–sequence stars (Opportunity 1). Exploration of these data in the time domain will reveal binaries and provide unprecedented views of the time–dependence in the accretion processes by which stars assemble. Further studies of the closest clusters containing high–mass stars would reveal the dynamics turning molecular clouds into stars (Op. 2). We can for the first time expose the most massive clusters of the Milky Way, constrain the Galactic star formation rate from first principles, and probe whether the Galactic Center black hole is required to power the enigmatic *Fermi/LAT* bubbles (Ops. 3 & 4). Only *SDSS* can provide the context in which future *JWST* observations of distant high–mass clusters must be interpreted (Op. 5). All of this research can be completed using the APOGEE spectrographs, ideally using telescopes in both hemispheres. However, much of our research focusses on early–type stars that are best explored at longer wavelengths. We therefore envision to build a new *K*–band multi–object spectrograph.

This Letter of Interest summarizes science programs that are detailed in the *Unbiased Views of Young Stars in the Milky Way* white paper (WP) written for AS4. It is backed by a significant collaboration (see bottom) that is open to additional interested partners.

1 Context

The next five years will see remarkable progress in the quantity and quality of data available to study optically revealed stellar populations. *Gaia* will provide parallaxes and proper motions to enable the calculation of robust membership probabilities and the precise location of sources within the HR diagram; *Kepler/K2* and *TESS* will have made available precise optical light curves to identify and characterize pre–main sequence variables (i.e., eclipsing binaries, accretion instabilities, disk occultation events, etc.); and *Lamost* will enable the derivation of reliable stellar parameters from low–resolution optical spectra for large numbers of objects over wide fields of view. As a result, when *SDSS*–IV concludes in ~ 2020, the data will already be available to revolutionize our understanding of the properties of optically revealed clusters and pre-main sequence stars.

By contrast, relatively few advances are expected in the next five years in our capacity to observe and understand the properties of the youngest embedded stellar populations. These are usually optically obscured by visual extinctions $A_V \gtrsim 10$ mag and largely invisible to missions like *Gaia*. For example, at distances ~ 1 kpc even stars of $\sim 3\,M_\odot$ then drop below detection thresholds $V \sim 20$ mag. By 2020 *JWST* will be in orbit, and *WFIRST* will be progressing towards launch. These missions target emission at long wavelengths that is less sensitive to extinction. They will provide dramatic advances in the photometric characterization of individual embedded protostars and planetary systems — but these telescopes will not provide detailed spectroscopic information to precisely diagnose the stellar and kinematic properties of embedded stellar populations. As a result, near–infrared multi–object spectroscopy, as for example enabled by the APOGEE spectrographs, will still provide an unmatched and critical capability for the study of star and planet formation. This would in particular hold if optimized *SDSS* hardware would permit multiple visits and allow to, e.g., explore time–dependent accretion phenomena.

Previous projects exploring young stellar objects (YSOs) have already made good use of the unique abilities of the *SDSS* system. Deeply embedded stars are currently being probed with APOGEE. Star formation (SF) projects in *SDSS*–III focussed on relatively nearby star formation in Perseus (d = 260 pc), Orion (420 pc), and NGC 2264 (800 pc). The observations were done as part of the IN–SYNC project lead by some of us. First results from this work (see our WP) demonstrate APOGEE's ability to constrain the properties of embedded stars with a very high precision (~ 50 K in $T_{\rm eff}$, ~ 0.15 dex in $\log(g)$, $\lesssim 1\,{\rm km\,s^{-1}}$ in radial velocities, $\sim 10\,{\rm km\,s^{-1}}$ in $v \cdot \sin(i)$, and ~ 0.2 in veiling). The *SDSS*–IV Young Cluster program targets further nearby regions like Taurus and the Pleiades, it returns to NGC 2264, and it conducts a major survey of young stars in Orion. But it also includes a first much more distant target, i.e., the W3/W4/W5 complex at 2 kpc distance.

Current and planned APOGEE programs towards embedded stars account for about 7 effective nights during *SDSS*–III, plus 16 effective nights that are still to be executed in *SDSS*–IV. This modest time allocation clearly shows that only a small fraction of the potential discovery space of SF projects will be explored until the end of *SDSS*–IV. We propose to increase this sample of young stars by about an order of magnitude using a set of observational programs (Sec. 2) that take advantage of existing, upcoming, and proposed hardware (Sec. 3).

2 Unique Science Opportunities

Our *After SDSS-IV* WP defines a systematic survey of Young Stellar objects (YSOs) in diverse star forming regions of the Milky Way. It takes advantage of the uniquely efficient and uniform near–IR multi–object spectroscopic capabilities of *SDSS*–APOGEE. We envision to divide the program in four main areas.

1. A Census of Nearby YSOs. APOGEE can constrain spectral variables (e.g., $T_{\rm eff}$, log(g), rotation, veiling) required to constrain theoretical models of early stellar evolution. These data allow estimations of mass and age of $\lesssim 1\,M_\odot$ YSOs within 1 kpc, e.g. by revealing the evolution circumstellar disks as a function of stellar properties. *A systematic survey of proto– and pre–main sequence stars with the SDSS's uniquely efficient and uniform multi–object spectroscopic capabilities would transform our understanding of the properties and processes encoded in young stellar photospheres in the same way that infrared photometric surveys with Spitzer and WISE transformed our understanding of the evolutionary sequence of young stellar objects.*

Provided appropriate *SDSS* hardware is available, this work will include ***unprecedented monitoring of YSO spectral properties in the time domain***. We would search for both short-term spectroscopic variability, luminous FU Ori and ExOr flares from low-mass stars, OMC1–like events from stellar mergers, and dynamic interactions in dense forming clusters by looking for shock–excited H_2, He II, and variability. We plan to enable dynamic scheduling to enable high cadence measurements. This could provide a spectroscopic follow-up of *LSST*–detected transients and variables in Galactic star forming regions.

Of order 90 nights (about 540 visits) are needed to sample regions at distances of < 1 kpc. We expect a yield of about 2×10^4 stars. An addition of 10 nights will provide follow up and characterization of binaries.

2. A study of the formation and early evolution of young clusters. One of our main plans is to survey embedded clusters in a generous sample of star forming complexes in both hemispheres, covering distances from 1 to 3 kpc. This has not been attempted before. We will determine the mean radial velocity and velocity dispersions of clusters, and compare this to velocity field of associated gas (molecular, atomic, and ionized). This is essential to understand the process of formation and early evolution of star clusters, and how some of them survive as dynamically stable entities like open and globular clusters. Also, we would have precious information on the interaction of stars and gas, to assess capital questions like the importance of triggering in the formation of massive associations. This will be highly complementary to work with the *JWST* which will provide excellent photometry but lack spectral information.

This science requires a total of 18 to 36 nights (108 to 216 visits; dependence on crowding implies 6 or 12 visits per plate). We expect a yield of $4-5 \times 10^4$ stars.

3. Extreme star–forming environments. We will reveal all high–mass stars in the Central Molecular Zone (CMZ), i.e., the inner $\sim$ 200 pc of the Milky Way. This will ultimately constrain the so–far unknown star formation history of the Galactic Center and reveal whether intense SF alone, and not the central black hole, might power the enigmatic *Fermi/LAT* bubbles. *SDSS* also has a unique potential to reveal the OB stars that power the $\sim$ 30 cardinal SF sites of the Milky Way evident in *WMAP* data.

About 20 nights are needed for this work (120 visits, 60 for each case: CMZ and OB star host complexes). We estimate a yield of about 3,000 OB stars. Estimation of yields for CMZ are ongoing.

4. The galactic SF rate from first principles. We envision to observe about $\sim 10^3$ OB stars in various stages of evolution along the Galactic plane. We expect our sample to be complete down to $d = 4$ kpc in the presence of foreground screening up to $A_H < 2$ mag. *SDSS* spectroscopy is the only efficient way to reveal obscured OB stars, invisible to Gaia. This sample will constrain the star formation rate in our neighborhood from first principles, and trace the local spiral arms.

This work can be done in about 7 nights (40 to 45 visits). Each visit is expected to provide > 200 targets, so we expect to observe under 10^4 spectra.

3 Required Hardware

Only *SDSS* can provide the context in which future *JWST* observations of distant high–mass clusters must be interpreted, ideally by using spectrographs in both hemispheres. Large fractions of the sky are needed to provide the proposed samples. Moreover, interesting massive star formation regions are located in both hemispheres and only by exploring them both we can constraint the star forming rate of the MW. The Galactic Center is accessible from the South. Therefore, the availability of both the APO and du Pont is highly beneficial for the work described here.

The scientific output of this project would be even higher if we could explore YSOs at longer wavelengths. For instance, the Conti–Hansen K-band classification scheme is well established for massive stars. Also, the K-band can provide crucial information on jets, outflows and shocks. The science output, while not strictly dependent on this, would be highly enriched with $R \sim 10^4$ spectra in the 2.0-2.2 μm range. Thus, we also provide our vision on to build a new K-band multiobject spectrograph using a single Teledyne HAWAII-H2RG array with a relatively low cost (<$2M). The instrument would be compact, based on a reduced spectral range and the scaling of instrument volume by the refraction index of Si at the K-band (see e.g. IGRINS@MacDonald Observatory). Moreover, a short fiber (1-2m limit) configuration is needed to avoid absorption. An immersion grating K-band spectrograph would provide practicality for short fiber runs and portability between facilities (see below). Granted, technological challenges will arise, but the instrument will be both innovative and will have unique scientific capabilities.

Although not critical, we point out that the project would benefit from having access to the ARC 3.5m (based on better sensitivity and plate scale despite a reduction in FOV) provided it is connected to the APOGEE fiber network. Also, we could use the NMSU 1.0m telescope for long term spectral monitoring.

Finally, we consider that a robotic fiber positioner would expand the parameter space of our projects. On one hand, we would be allowed to obtain relatively short exposures for bright targets, but also, as a good fraction of our fields present significant crowing, the current fiber–plug configuration would require of frequent plate changes. Further, ***a robotic fiber positioner would critically simplify multi–epoch observations required for time–domain aspects of our program***, such as accretion variability and spectral line binaries. Such a device would massively expand the parameter space accessible to the *SDSS*.

4 The Young Stars Survey Team

Primary Contacts:
Carlos Román-Zúñiga (croman@astro.unam.mx)
Jens Kauffmann (jens.kauffmann@gmail.com)
John Bally (john.bally@colorado.edu)

Signatures in alphabetical order:

1. Héctor Arce, Yale University,
2. John Bally, University of Colorado,
3. Jura Borissova, Universidad de Valparaiso, Chile,
4. Irene Cruz-González, Instituto de Astronomía, UNAM, Mexico,
5. Kevin Covey, Western Washington University,
6. Nicola Da Rio, University of Florida,
7. Juan José Downes-Wallace, Centro de Investigaciones de Astronomía, Venezuela,
8. J. G. Fernández-Trincado, Observatoire de Besançon,
9. Eric D. Feigelson, Penn State University,
10. Roberto Galván-Madrid, Instituto de Radioastronomía y Astrofísica, UNAM,
11. Y. Gómez Maqueo Chew, Instituto de Astronomía UNAM,
12. Jesús Hernández, Instituto de Astronomía, UNAM,
13. Lynne Hillenbrand, California Institute of Technology
14. Jens Kauffmann, Max-Planck-Institut für Radioastronomie, Bonn, Germany.
15. F. Nakamura, National Astronomical Observatory of Japan, Mitaka, Tokyo, Japan,
16. Christian Nitschelm, Universidad de Antofagasta, Chile,
17. Aina Palau, Instituto de Radioastronomía y Astrofísica, UNAM,
18. Kaike Pan, New Mexico State University,
19. Tushara Pillai, Max-Planck-Institut für Radioastronomie, Bonn, Germany,
20. Mudbi Rahman, John Hopkins University,
21. Carlos Román-Zúñiga, Instituto de Astronomía, UNAM,
22. Alexandre Roman-Lopes, Universidad de la Serena, Chile,
23. Jianrong Shi, Chinese Academy of Sciences,
24. Michael Strutskie, University of Virginia, Charlottesville,
25. Jonathan Tan, University of Florida,
26. Mauricio Tapia Ibargüengoitia, Instituto de Astronomía, UNAM,
27. Alan Watson, Instituto de Astronomía, UNAM,
28. Alycia Weinberger, Carnegie Institution for Science
29. Jason Ybarra, Bridgewater College, Virginia