APOGEE: The Apache Point Observatory Galactic Evolution Experiment

C. Allende Prieto¹, S. R. Majewski², R. Schiavon³, K. Cunha⁴, P. Frinchaboy⁵, J. Holtzman⁷, K. Johnston⁸, M. Shetrone⁹, M. Skrutskie², V. Smith⁴ and J. Wilson²

¹ Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Surrey RH5 6NT, UK
² Department of Astronomy, University of Virginia, P.O. Box 400325, Charlottesville, VA 22904–4325, USA
³ Gemini Observatory, 670 North A‘ohoku Place, Hilo, HI 96720, USA
⁴ National Optical Astronomical Observatory, Casilla 603, La Serena, Chile
⁵ NSF AAF Fellow, Univ. of Wisconsin-Madison, Department of Astronomy, 4506 Sterling Hall, 475 N. Charter Street, Madison, WI 53706, USA
⁶ Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation (NSF).
⁷ New Mexico State University, Las Cruces, NM 88003, USA
⁸ Astronomy Department, Columbia University, New York, NY 10027, USA
⁹ McDonald Observatory, University of Texas, Austin TX 78712, USA

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APOGEE is a large-scale, NIR, high-resolution ($R \sim 20,000$) spectroscopic survey of Galactic stars. It is one of the four experiments in SDSS-III. Because APOGEE will observe in the $H$ band, where the extinction is six times smaller than in $V$, it will be the first survey to pierce through Galactic dust and provide a vast, uniform database of chemical abundances and radial velocities for stars across all Galactic populations (bulge, disk, and halo). The survey will be conducted with a dedicated, 300-fiber, cryogenic, spectrograph that is being built at the University of Virginia, coupled to the ARC 2.5m telescope at Apache Point Observatory. APOGEE will use a significant fraction of the SDSS-III bright time during a three-year period to observe, at high signal-to-noise ratio ($S/N > 100$), about 100,000 giant stars selected directly from 2MASS down to a typical flux limit of $H < 13$. The main scientific objectives of APOGEE are: (1) measuring unbiased metallicity distributions and abundance patterns for the different Galactic stellar populations, (2) studying the processes of star formation, feedback, and chemical mixing in the Milky Way, (3) surveying the dynamics of the bulge and disk, placing constraints on the nature and influence of the Galactic bar and spiral arms, and (4) using extensive chemodynamical data, particularly in the inner Galaxy, to unravel its formation and evolution.

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1 Introduction

Our knowledge of the structure, formation and evolution of galaxies is built upon observations of numerous galaxies as well as on detailed measurements in the Milky Way. Only for the Galaxy can we quantify precisely the basic properties of individual stars from parallaxes, proper motions and high-resolution spectroscopy. Only for the Milky Way we can make a census of minority stellar populations which, as in the case of the stellar halo, can be central to understanding the earliest epochs of galactic formation. In addition, the spatial resolution of gas and dust maps available for the Galaxy is orders of magnitude better than for extragalactic systems.

As a result of developments in instrumentation over the last decades, high-resolution spectroscopic studies have become more and more precise, involve larger samples, and reach fainter magnitudes. These advances have made it possible to carry out a thorough study of the stellar populations in the solar neighborhood and measure high precision chemical abundances for dozens of elements and hundreds of stars. These observations have revealed, among other things, a clear dichotomy between the chemical patterns in thin- and thick-disk stars, despite their overlapping distributions in phase space.

Progress has probably been even more spectacular for studies using lower spectral resolution, thanks to massive multiplexing on fiber spectrographs such as those used in the Sloan Digital Sky Survey (SDSS; York et al. 2000), which operate at $R = 2,000$. The information per spectrum is more limited, but this is compensated by deeper and much larger samples of stars. More than half a million stars have already been observed in the course of the SDSS, and this number will double over the next three years. Several tens of thousands of stellar spectra have already been analyzed in recent studies from SDSS (Allende Prieto et al. 2006, Ivezić et al. 2008), and higher resolution ($R \sim 7,500$) spectra, over a limited spectral window, are now becoming avail-
able from the Radial Velocity Experiment (RAVE; Zwitter et al. 2008). This allows a thorough characterization of the properties of the Milky Way stellar halo, and provide information on the thick disk over a wide range of galactocentric distances. Now we know that the thick-disk stars are old, but intermediate in age between the halo and the thin disk, and that the thick disk does not show radial abundance gradients such as those well-known in the thin disk (Allende Prieto et al. 2006).

In stark contrast with the fast pace at which we have been able to make progress in our exploration of the outer Galaxy at low resolution and the steady accumulation of high resolution information on nearby stars, the situation for understanding the non-local, inner Milky Way at any resolution has been much less favorable. The high extinction in the Galactic mid-plane and towards the Galactic center severely complicates observational studies at traditional optical wavelengths. Spectroscopic studies of the Galactic bulge have been limited to small numbers of stars — almost exclusively in Baade’s window. The Apache Point Galactic Evolution Experiment (APOGEE) is targeted to dramatically change this situation by using highly-multiplexed near-IR high-resolution spectroscopy to pierce through dust and probe stars in the central parts of the galaxy at high resolution. In addition, APOGEE will push the systematic, high resolution, high throughput spectroscopic study of Galactic stars into the outer Galaxy, creating a uniform spectroscopic database for stars in all populations of the Milky Way. Such homogeneous but extensive datasets are necessary to produce an integrated picture of the chemical and kinematical evolution of our home galaxy.

2 Why in the H band? Why now?

We have mentioned that the most serious problem to access the central parts of the Galaxy is dust obscuration. Dust absorption in the H band (∼ 1.6 μm) is more than 5 times smaller than in the optical (e.g., $A_H/A_V = 0.16$). A second key fact is that near-IR instrumentation has now reached the level of maturity necessary to make wide-field, multiplexed high-resolution spectroscopy at these wavelengths both feasible, and very efficient. In just a year of observing time (bright time during three years) APOGEE will make a substantial leap in the total number of available, high resolution optical or NIR spectra for Galactic stars in general (about two orders of magnitude!).

In addition, several other factors make this an ideal time to undertake an H-band survey of giant stars in the Galaxy with the Sloan telescope:

- K-type giant stars down to the magnitude of the red clump are bright enough in the H band that the sensitivity of current IR detectors and throughput of NIR gratings allow us to reach the central parts of the Milky Way at $R \sim 20,000$ and $S/N = 100$ with a mid-class telescope (e.g., 2.5-m aperture).
- A low atmospheric extinction in the infrared makes it possible to access the Galactic bulge from the Northern Hemisphere (Apache Point, in particular).
- A complete catalog of sources down to $H \sim 15$ is available to carry out an unbiased target selection (2MASS; Skrutskie et al. 2006).
- The software/hardware infrastructure deployed for the SDSS and the experience gained in large survey operations provide a foundation on which efficiently to build a massive spectroscopic data set and make it accessible to the scientific community.
- The schedule for the European mission Gaia plans a release of its comprehensive astrometric catalog by 2017 (parallaxes and proper motions for 1 billion stars with an accuracy of $\sim 10 - 25 \mu$arcsec$^1$). Thus, we can assemble complete kinematical data and accurate distances for stars for which APOGEE will derive precision chemistry and radial velocities.

In addition, the H-band accesses a part of the spectral energy distribution where the continuum is form deepest and which contains lines formed close to LTE conditions for multiple interesting elements, including C, N, O, Fe, several $\alpha$ elements, iron peak elements, and odd-Z elements.

3 Scientific objectives

High resolution spectroscopy allows the characterization of a resolved stellar population in exquisite detail. The chemical compositions of FG-type stars can be routinely derived from optical spectra for many elements with a precision better than 0.04 dex (see, e.g. Bensby et al. 2007; Fuhrmann 2008; Reddy et al. 2007). In the NIR, the presence of significant telluric absorption, and emission features, mainly OH, from high atmospheric layers, complicates matters, but previous studies in this band have successfully determined chemical abundances for an array of elements with a relative uncertainty of $< 0.1 \text{ dex}$ (e.g. Cunha & Smith 2006, Rich & Origlia 2006, Meléndez et al. 2008). Given that APOGEE will have considerable advantages regarding calibration being such a large and homogeneous survey, we expect to be able to reach this mark easily.

By obtaining, with this kind of precision, the chemical abundances for the elements C, N, O, Mg, Al, Si, Ca, Ti, Cr, Fe and Ni for all surveyed stars, as well as Na, S, V, Mn, Co and other elements for brighter stars, APOGEE will be able to dissect the chemical history of the different Galactic stellar populations. APOGEE will not only map the metallicity distribution functions and differential abundance patterns for these elements as a function of Galactic position, but measure their relative rates of enrichment, correlations

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1 Note that Gaia will fly a high-resolution spectrograph. However, it will operate at shorter wavelengths (847-874 nm) and, with an integration time limited by the continuous rotation of the satellite, chemical abundances will only be measured down to $V < 12 - 13$ (Wilkinson et al. 2005), equivalent to $H < 9$ for a late-type giant.
with kinematics, and the chemical/kinematical relationships between populations.

A major objective of APOGEE is to penetrate the bulge of the Milky Way, uncover the dynamics of the Galactic bar, and find out its connection to the dynamics of the disk. The presence of a bar in the Milky Way has been inferred from photometry (see López-Corredoira et al. 2007 and references therein). Radial velocities, which should be free of systematic errors at a level \( < 1 \text{ km s}^{-1} \), can be extracted by cross-correlation from the APOGEE spectra, and should confirm the presence of the bar, as well as provide, by comparison with dynamical models, fair estimates of its mass and hints about its origin.

APOGEE will also target areas of the Milky Way other than the bulge. Although the local thin disk, thick disk, and halo have been studied before, APOGEE will reach other parts of the disk far from the solar circle, and obtain a larger and homogeneous sample of high resolution spectra of distant halo giants. Most importantly, APOGEE will, for the first time, place the measurements for all the stellar populations in the Galaxy under the same system, removing systematic effects that plague existing studies based on compiling observations from different instruments and analysis protocols.

Another goal of the survey will be to measure the rotation curve of the Milky Way. Using stars will make it unnecessary to base the distance estimates on the assumption of circular motion as it is done for observations of gas at longer wavelengths, for we can rely on the spectroscopic parallaxes derived directly from measured surface gravities, metallicities and temperatures. In addition, from these well-established spectroscopic parallaxes we can explore the 3-D distribution of dust, expressed in photometric colors.

4 Instrument design

An \( H \)-band survey balances the need to efficiently punch through dust, avoids a large thermal background, takes advantage of the peak of the red giant star spectral energy distribution, operates effectively during the more abundant and available 2.5-m bright time, and accesses a part of the spectral energy distribution that contains lines for multiple interesting elements. Fig. 1 illustrates with the spectrum of Arcturus (K1.5 III) some of the lines available over the tentative spectral window for APOGEE. The figure also shows which regions are most affected by telluric absorption/emission; these have already been removed in the displayed stellar spectrum.

The goal of precision velocities and abundances determines that the instrument resolution be of order \( R = 20,000 \). This resolution will enable an accurate location of the continuum, resolve crowded line packing, make possible efficient removal of telluric absorption/emission, and permit the derivation of abundances for key desired elements with \( < 0.1 \) dex precision for stars as metal-poor as \([\text{Fe/H}] = -2.0\), provided a signal-to-noise ratio \((S/N)\) of 100 per pixel.

Typical target densities for potential APOGEE targets (e.g., red, evolved stars to \( H \sim 13 \)) within the SDSS telescope field-of-view are in the thousands towards the Galactic center, and 300-900 at the anticenter (see Fig. 2). Survey efficiency pushes toward the maximal possible number of fibers, but maximal packing of spectra across 2048 expected
detector pixels limits the number of fibers to about 300. This expected practical limit means that generally every fiber can be filled with a primary APOGEE target for low latitude pointings, and makes it practical to observe 100,000 stars in three years of bright time. While $H \sim 13$ is the nominal expected limit at $S/N = 100$ for what will typically be three hour exposures, deeper probes will also be possible for longer integration times, enabling access to the more distant halo as well as the most deeply dust-buried disk stars.

The preliminary instrument design for APOGEE considers two Raytheon $2048 \times 2048$ HgCdTe detectors and a VPH grating, sampling the 1.52–1.58 $\mu$m and 1.62–1.68 $\mu$m windows with a resolving power $R \sim 20,000$. A summary of the nominal instrument specifications is provided in Table 1. The entire instrument will operate at cryogenic temperatures to reduce the thermal background. Given the expected mass and size, it will be mounted on a bench with light fed from the 2.5m telescope by $H$–band optimized dry fibers. A bench-mounted spectrograph has the additional advantage of improved stability, and more reliable calibrations (flatfields or Th-Ar spectra). Precise wavelength calibration will generally be afforded by the prominent airglow lines, while telluric absorption will be mapped by hot stars included in each integration.

5 Expected results

Automated pipelines for data reduction will be used to process a uniform fashion all the APOGEE spectra. The survey will generate an estimated 15 Tb of raw data, and the processing and distribution strategies will rely on the expertise accumulated by the SDSS over the last decade.

The next step, the determination of radial velocities and chemical abundances, will necessarily be performed by automated pipelines as well. Spectral synthesis, as opposed to integrated equivalent widths, will be used, given the frequent overlapping of neighboring transitions. The ongoing SEGUE survey (Sloan Extension for Galactic Understanding and Exploration; Yanny et al. 2008, in preparation), part of SDSS-II, precedes us, but the challenge for APOGEE will be to extend its high-throughput data reduction pipeline to high-resolution spectroscopy. A carefully devised calibration plan, including overlapping fields and coordination with SEGUE, is also now under development.

We anticipate public releases of APOGEE data including: (1) fully calibrated, 1-D spectra of each targeted star, (2) radial velocities precise to better than 1 km s$^{-1}$, (3) atmospheric parameters ($\log g$, $T_{\text{eff}}$, [Fe/H]), and (4) abundances for numerous elemental species. The resulting catalog will be used to produce:

- A 3D map of abundances across the Galactic disk, bar, bulge and halo, probing for correlations between chemistry and kinematics.
- Constraints on the initial mass function and star formation rate of the bulge and the disk as a function of radius derived from, e.g., [$\alpha$/Fe] abundance trends.
- A firm characterization of the bar of the Milky Way.
- An accurate measurement of the Galactic rotation curve, which can be used to constrain the dark matter density profile.

APOGEE will be diving into uncharted territory, and therefore unexpected findings are to be expected, such as serendipitous discoveries of peculiar, or extreme, stars and rare chemodynamical stellar populations. The current road map calls for a very fast instrument development phase to be on the sky by 2011.

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