Multi-Dimensional Galactic Dust: Kinematics and Optical Properties

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Summary

SDSS-APOGEE has been stunningly successful in its mission to obtain radial velocities and chemical signatures of over 100,000 red giants in the Galactic disk, bulge, and halo. We propose to use an expanded sample of these stars to probe the Galactic dust along the line of sight in 3-D, through spectral absorption features (diffuse interstellar bands, DIBs) and continuum absorption (parameterized by R_V). Near-IR spectra provide unique insights into the interstellar medium (ISM) because: (1) the 1.53 micron DIB feature is a powerful tracer of dust column density and velocity, (2) the spectral types of stars can be determined in an unbiased way, even behind several magnitudes of A(V) extinction, and thus (3) such stars can be used to infer the dust extinction curve. These measurements will map R_V in 3-D, determine the Milky Way ISM's rotation curve and deviations from circular rotation, and reveal how gas flows into and out of molecular clouds out to at least 4 kpc. Accomplishing these goals requires spectra of 100,000 additional stars with $|b| < 5°$, over both the northern and southern hemispheres, uniformly distributed throughout this volume.

Scientific Motivation

By studying the ISM absorption to stars with *Gaia* or other distance estimates, we will be able to dissect the ISM in 3-D, and even in 4-D when combined with DIB velocities. These goals require a sample of stars uniform in angle and distance, which dovetails with the needs of the DISCO LOI and complements the more densely sampled but non-contiguous footprint of the existing APOGEE surveys. We lay out three major research directions this program will enable.

Dust Grain Properties In 3-D

The dust extinction curve is largely characterized by a single number, $R_V = A(V)/E(B-V)$, which is sensitive to the dust grain size distribution and composition, and must be known so that optical observations can be properly corrected for extinction. Combination of the parameters of reddened stars from APOGEE with existing broadband photometry (and forthcoming DECam/LSST photometry) allows the extinction curve to determined in a precise and unbiased way (Figure 1; Schlafly et al. 2016). The proposed survey will enable us to map R_V at 100 pc resolution throughout the entire $|b| < 5°$ sky, and generate the definitive 3-D resolved R_V measurement of the Galactic plane. The R_V map will address important astrophysical questions: What physical processes determine the grain size distribution? Does R_V correlate with gas density, ISM metallicity, or the interstellar radiation field? Do shocked regions of the ISM shatter dust grains and steepen the extinction curve? These issues have implications not only for the study of Galactic dust but also for dust in higher redshift galaxies and SNe.

Dust Kinematics

Different phases of the Galactic ISM have been observed on scales both large and small with a variety of tracers. In total, though, the ISM's high-dimensional phase space (3-D position, 3-D velocity, chemistry, etc) has been irregularly explored − e.g., we can access the 3-D spatial distribution of dust but not its kinematics. In addition, one of the phases of the ISM that has been most difficult to trace on large scales is the spatial distribution of the tiniest dust grains − very carbon-rich molecules that comprise a substantial fraction of the interstellar carbon budget. Fortunately, APOGEE's high-resolution, IR spectra enable high precision measurements of the velocity field of the 1.53 micron DIB, which is strikingly well correlated with the bulk of interstellar dust (Zasowski et al. 2015a,b). This new approach is a fundamentally new measurement of the ISM's phase space, and one that is uniquely accessible by APOGEE (Figure 2).

This program will use DIB measurements through the well-sampled regions of Galactic dust to answer some of the most uncertain questions facing galactic chemical evolution today: What impact do radial dust flows have on the chemical gradients in the stellar populations? What happens to dust at the disk/halo interface, and how do infall/outflows contribute to disk star formation?

Molecular Cloud Formation/Dissolution

Stars form from giant molecular clouds (GMCs), but we have very little consensus on how molecular clouds form. Agglomeration of smaller clouds, flow collision, Galactic-scale shocks, and gravitational instability are all used to describe how GMCs form, but we have no measurements of how gas in the neutral regime ($A(V) < 1$) kinematically gathers into molecular clouds ($A(V) > 2$) and then stars. Furthermore, we do not fully understand how GMCs are disrupted; only a small fraction of molecular clouds form into stars, and thus they must be destroyed by a stellar feedback process we do not understand in detail.

The 1.53 micron DIB, an excellent tracer of gas over a huge *A(V)* range, is the best tool for measuring this process directly. By measuring the strength of this DIB through GMCs, we can measure not only how column density increases with distance, but also the radial flow of the cloud along the line of sight (Figure 3) — exploding clouds have a strong positive correlation between distance and radial velocity, and collapsing clouds have a strong negative correlation. We propose here to observe giants with APOGEE *through* many GMCs across a range of ages, sizes, masses, star formation rates, and environments out to about 4 kpc. With the DIBs extracted from these data, we can determine whether GMC growth is related to Galactic structure on large scale, and the rate at which GMCs form and dissipate across broad swaths of parameter space.

Program Description

The legacy of this program will be *the* definitive 3-D dust velocity and extinction curve maps for the next decade. Achieving this goal calls for complete coverage of the Galactic plane with $|b| < 5°$ (north and south), with uniform coverage in both angle and distance to create homogeneous 3-D maps. We highlight the similarities between these requirements and those described by the DISCO LOI, for a fieldplan strategy so beneficial to both large projects.

A robust ISM map requires a spatial volume resolution of about 100 pc, which is roughly the separation between local molecular clouds and will allow spiral arms to be resolved. Each resolution element needs roughly 10 stars, for a total of 100k stars within 4 kpc. This corresponds to a target density of about 30 stars / deg^2, which is roughly comparable with the fiber density per plate in the north, and half the fiber density of the southern plates. This target density is sufficient for the kinematical mapping of GMCs and of large-scale dust flows within 4 kpc. Without a robotic (re-)positioner or other fiber switching mechanism, this strategy would require approximately 500-700 hours, assuming APOGEE's current efficiency, depending on local density of targets and availability of fiber switching. We would be very interested in such a mechanism to increase the sample density, particularly in regions of highly variable extinction in order to map this structure.

This program will benefit from targeting very similar stars as the APOGEE-I and APOGEE-II surveys: red clump (RC) and red giant branch stars. For an RC star at a distance of 4 kpc and an *E(B-V)* of 1.5, a 1-hour exposure corresponds to a S/N of 40. The existing APOGEE target selection strategy will be sufficient, with the following modifications: First, like DISCO, S/N=100 spectra are not required, since the R_V and DIB measurements do not require parameters or abundances more precise than ASPCAP or *The Cannon* can deliver at lower S/N. Second, *Gaia* parallaxes will be available starting in 2017, which will allow us to effectively exclude dwarf stars and to select a more uniform giant sample in 3-D space. *Gaia* parallaxes will have roughly 20% accuracy at 3 kpc for an RC star with *E(B-V)* = 1.5, well matched to our program, and all targets will have prior distance estimates from PanSTARRS, 2MASS, and other photometric datasets as well.

An exciting additional possibility is a deeper survey focusing towards the Galactic center, where R_V is known to have extreme variations and where the atomic and molecular ISM is known to have non-circular rotation. At these distances and extinctions, *Gaia* parallaxes would no longer be reliable, so RC stars would form the bulk of the sample (to obtain precise distances). Reaching the same S/N as in the disk-focused, 4-kpc survey component would require 16-hour exposures. Maintaining the same target density with these fainter targets within $|l|<20°$ would require approximately twice the time as the 4-kpc survey; small groups of fields within a more restricted longitude range could also be used, at a loss of homogeneity but with a reduced need for time.

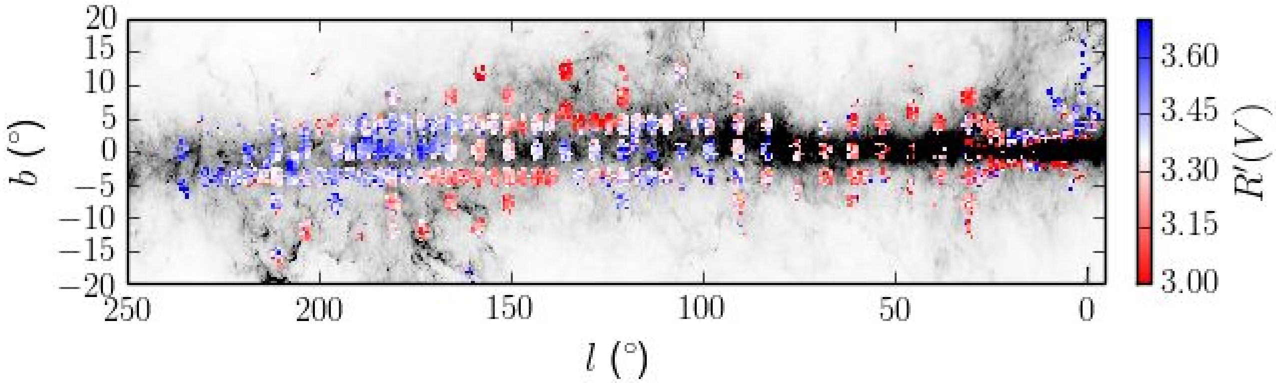

Figure 1. Angular map of R_V, derived from the combination of APOGEE parameters and optical/IR photometry (Schlafly et al. 2016).

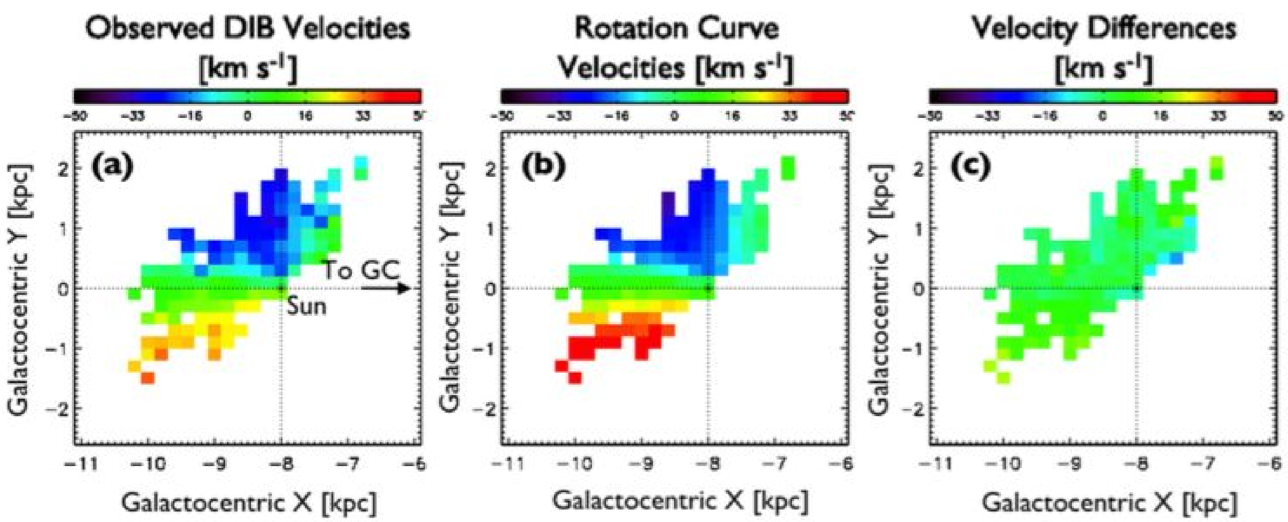

Figure 2. Face-on view of the local dust velocity field, derived from the combination of APOGEE DIB measurements (Zasowski et al. 2015) and the PS-1 dust map (Schlafly et al. 2014, Green et al. 2015), compared to a circular rotation curve (Clemens 1985). Figure from Zasowski et al. (2016).

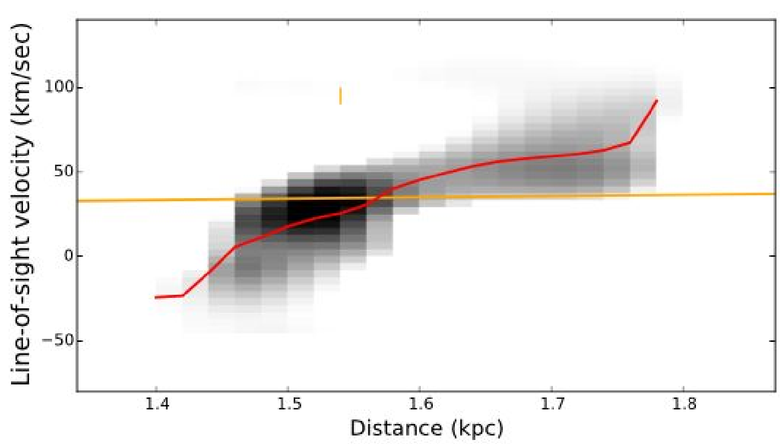

Figure 3. Distance-velocity diagram of the Rosette molecular complex, derived from APOGEE data, including DIB measurements (Tchernyshyov et al, in prep.). The orange line is the velocity expected at this position from a flat rotation curve.