A Census of Local Group Ultraviolet Dust Extinction Curves

Karl D. Gordon, STScI, kgordon@stsci.edu, 410-338-5031
Geoffrey Clayton, Louisiana State Univ., gclayton@fenway.phys.lsu.edu
Julianne Dalcanton, Univ. of WA, jd@astro.washington.edu
Bruce Draine, Princeton Univ., draine@astro.princeton.edu
Derck Massa, STScI, massa@stsci.edu
Karl Misselt, Univ. of AZ, misselt@as.arizona.edu
Karin Sandstrom, MPIA, sandstrom@mpia.de
UJ Sofia, American Univ., sofia@american.edu
Lynne Valencic, NASA/GSFC, lynne.a.valencic@nasa.gov
Michael Wolff, Space Science Inst., mjwolff@spacescience.org

Summary

Interstellar dust plays a central role in shaping the detailed structure of the interstellar medium, thus strongly influencing star formation and galaxy evolution. Ultraviolet extinction curves provide one of the main pillars of our understanding of interstellar dust while also being one of the limiting factors when interpreting observations of distant galaxies. Our observational picture of extinction curves is strongly biased to nearby regions in the Milky Way. However, the few extinction curves measured in the Magellanic Clouds show curves that are quite different from those seen in the Milky Way. We propose an observational program to obtain a census of ultraviolet dust extinction curves in the Local Group by measuring large, statistically significant samples of extinction curves in each Local Group galaxy. This program requires sensitive medium-band UV and blue-optical imaging and followup R $\sim$ 1000 spectroscopy of 1000's of sources. This census will, for the first time, provide a full census of dust and its variation with environment and galaxy type. It would simultaneously generate one of the largest ultraviolet spectral libraries ideal for a range of hot star studies. Such a census will revolutionize our understanding of the dependence of dust properties on local environment providing both an empirical description as well as strong constraints on dust grain and evolution models.

Background

Dust in the interstellar medium plays a central role in star formation and galaxy evolution. It helps shape the detailed structure of the interstellar medium (ISM), thereby directly influencing the process of star formation. It provides crucial shielding in molecular clouds and is the main formation site for molecular hydrogen. A thorough understanding of interstellar dust in galaxies in the local universe is needed to better understand the properties of dust itself as well as enable a clearer picture of star formation in galaxies.

The presence of dust is easiest to observe in the ultraviolet (UV), where it strongly absorbs and scatters photons, and in the infrared, where the absorbed energy is re-emitted through non-equilibrium (near- and mid-IR) and equilibrium (far-IR and submm) processes. The effects of dust on the UV (and optical/near-IR) spectrum of a background star is often

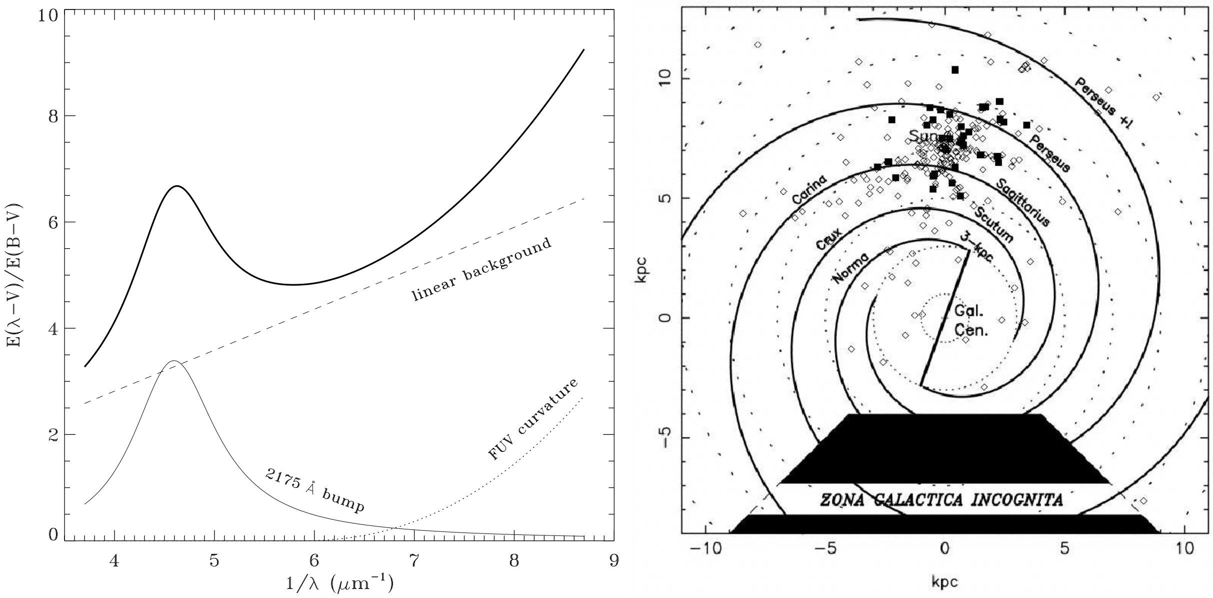

Figure 1: (a, left) All measured UV extinction curves can be decomposed into 3 components; a linear background, the 2175 Å bump, and a FUV curvature term. Figure from Fitzpatrick (1999). (b, right) The distribution of known Milky Way extinction curves is plotted projected onto the plane of the Galaxy. Figure from Valencic et al. (2004).

characterized by an extinction curve. Extinction curves are straightforward to measure using stars as these curves are simply the ratio of a reddened and unreddened star with the same surface physics (spectral type and metallicity). These curves combine the effects of dust absorption and scattering into a single measurement and show, among other features, the largest dust feature, the 2175 Å extinction bump (see Fig. 1a).

Our current view of dust is based, to a considerable extent, on measurements of UV dust extinction curves. Currently, there exist around 450 such extinction curves measured at spectroscopic resolution in the UV. Spectroscopic resolution is needed to produce high quality extinction curves that are not biased by spectral mismatches between the reddened and unreddened stars. These curves are mainly based on extensive International Ultraviolet Explorer (IUE) spectra taken in the Milky Way and the Magellanic Clouds. The IUE archive has been systematically studied and ∼400 extinction curves measured for the Milky Way (MW) (Valencic et al., 2004; Fitzpatrick & Massa, 2007). Almost all of these MW curves roughly can be described by a single parameter R(V) [= A(V)/E(B-V)] dependent relationship (Cardelli et al., 1989; Valencic et al., 2004), with a few outliers (Clayton et al., 2000; Valencic et al., 2003). The distribution of these extinction curves is shown in Fig. 1b and clearly illustrates that our knowledge of UV dust extinction curves is limited to just the ∼2 kpc around the Sun's location in the Milky Way.

The Magellanic Clouds provide the nearest galaxies in which we can easily measure dust extinction at different positions through a galaxy. Due to the relative faintness of stars

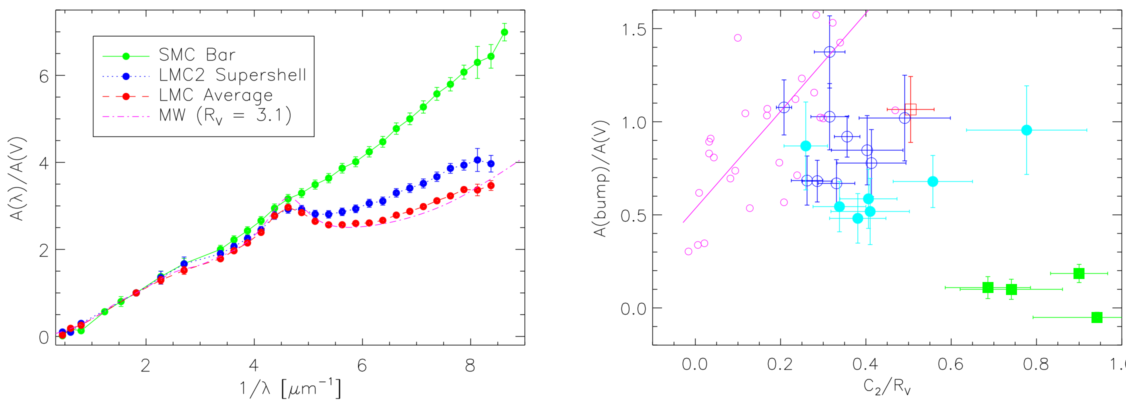

Figure 2: (a, left) The average MW, LMC and SMC extinction curves are shown. Figure from Gordon et al. (2003).
(b, right) The deviation of the LMC/SMC curves from the MW R(V) dependent relationship is shown along with the anti-correlation between the 2175 Å bump and UV slope ($C_3/R(F)$). The MW R(V) dependent relationship is sown as purple circles and line, LMC average sample are open blue circles, the LMC LMC2 supershell sample are closed cyan circles, the SMC AzV 456 sightline is an open red square and the SMC Bar sample are closed green squares. Figure from Gordon et al. (2003).

in these galaxies, the number of UV curves in both galaxies is much smaller than in the MW with 20 for the LMC (Misselt et al., 1999) and 9 for the SMC (Gordon & Clayton, 1998; Maíz Apellániz & Rubio, 2012). The majority of these curves deviate strongly from those seen in the MW. The most extreme variations are found in the SMC Bar where the curves have no 2175 Å bump and a very steep UV slope, yet in this same galaxy there are sightlines with strong 2175 Å bumps. Fig. 2a shows the average LMC and SMC curves with the average curve for the MW. The deviations of the LMC and SMC curves from the MW R(V) dependent relationship are shown in Fig. 2b demonstrating hints of an anti-correlation between the strength of the 2175 Å bump and the UV slope. In a the more distant M31, there is a detection of a possibly weaker than MW 2175 Å bump in M31 (Bianchi et al., 1996). These extragalactic extinction curves illustrates that the true range of properties of dust in the Universe is larger than our current understanding of MW dust and that observations across the faces of nearby galaxies are our current best measure of the true range of UV properties of dust.

The importance of measuring the true range of dust extinction curves is based on the fact that these curves provide the main basis for our understanding of dust grains, by providing constraints on their composition, size, and shape (Clayton et al., 2003; Weingartner & Draine, 2001; Zubko et al., 2004; Draine & Li, 2007). Our current models of dust grains are non-unique, because of the limited number of observational constraints. Progress on modeling dust grains will require a combination of laboratory studies on candidate materials, and, most importantly, improved observational constraints. In the observational area, one area

Table 1: Program Summary

Capability	**Value**
galaxies	M31, M33, LMC, SMC, NGC 6822
Photometric Survey	
band central wavelengths	1500, 1900, 2200, 2500, 3500, 4100
spatial resolution	FWHM $\sim$ 0.1”
sensitivity	S/N = 20, B5V star
survey area (5 galaxies)	70 sq. deg.
Spectroscopic Survey	
spectral resolution	1000
spectral coverage	1150–3000 Å
sensitivity	S/N = 50, B5V star
spectra needed	1200/galaxy

clearly promising to help better understand dust grains is the study of the correlation between observed dust properties and local environment. For example, the strength of the 2175 Å bump may be anti-correlated with the local massive star formation (Gordon & Clayton, 1998; Gordon et al., 2003).

Proposed Program

We are proposing a program to take a census of the dust properties in all the Local Group galaxies with significant dust. The set of measurements needed would be on the order of 1000 extinction curves in each galaxy. This would require UV spectra of on the order of 1200 massive stars (O5 - B5 spectral types) in each galaxy to provide measurements of 1000 sightlines and 200 comparison, unreddened stars (for direct comparison and constraints on stellar atmospheres). The sample size is set to provide a good sampling of the full range of dust extinction curves (50 sightlines) in broad spatial bins in each galaxy (20 spatial bins per galaxy). The Local Group galaxies to be targeted would be M31, M33, LMC, SMC, and NGC 6822. This sample of galaxies includes a massive spiral (M31), one dwarf spiral (M33), one dwarf disturbed spiral (LMC), and two irregular galaxies (SMC, and NGC 6822). These galaxies span a range of metallicities from somewhat above solar (M31) to around 1/5 solar (SMC). These galaxies have very low Milky Way foreground dust ensuring that the dominant dust signal is internal to target galaxy. These are well studied galaxies and the local environment region-by-region in each galaxies will be quantified using existing observations (e.g., ground-based H-alpha imaging for star formation, Spitzer/Herschel IR imaging for the average radiation field, Spitzer AGB star counts for dust production sites, and Hubble color magnitude diagrams for star formation history).

None of the Local Group galaxies targeted have 1000 massive, *reddened* stars identified in them. Thus, our proposed program would include a wide-field survey of the 5 galaxies using medium-band UV and blue-optical filters. The survey would include the full face of each galaxy to ensure the full extinction variation in each galaxy is probed. The filters would include 4 filters in the UV with central wavelengths of 1500, 1900, 2200, and 2500 Å to photometrically probe far-UV extinction (1500 Å) and the strength of the 2175 Å bump (other 3 filters). The combination of these 4 UV filters with blue-optical filters probing the Balmer jump (roughly Strömgren u and v) would provide high quality photometric spectral types and a rough measurement of the UV extinction curves (Massa et al., 1983). Additional bands at longer optical and near-infrared wavelength would improve the photometric spectral types and dust A(V) measurements, but are not strictly necessary. The spatial resolution needed is determined by crowding issues and is on the order of 0.1" (the PHAT HST M31 multi-cycle treasury is getting good results at this resolution). The sensitivity needed is set by need to reach B5V, the coolest, main sequence star that has enough far-UV flux to provide high quality extinction curves. Reaching to mid-B main sequence stars is required to probe less crowded environments as more massive O stars will generall be in more crowded regions and probe only the cores of star forming regions. We estimate a signal-to-noise of 20 in each band is needed to provide good photometric spectral types and dust A(V) measurements. The areas of each galaxy would be LMC (50 sq. deg.), SMC (15 sq. deg.), M31 (3 sq. deg.), M33 (1 sq. deg), and NGC 6822 (0.5 sq. deg.) for a total survey area of 70 sq. deg. The exposure time per point would be least in the largest galaxies as they are the closest.

Targets for the spectroscopic survey would be chosen from the best quality candidates from the photometric survey. The UV spectroscopy would need to have high enough signal-to-noise to provide the ability to obtain UV spectral types (Smith Neubig & Bruhweiler, 1997). Using ground-based telescopes to obtain classical blue-optical spectra is difficult given typical crowding of sources in these galaxies (especially M31, M33, & NGC 6822). A spectral resolution of 1000 provides high enough resolution to measure stellar features. The requested spectral range would be from 1150–3000 Å. This provides region around the 2175 Å bump as well as the far-UV region needed to determine UV spectral types. This region also include the Lyα line, providing high-quality measurements of the HI column density for these sightlines that would be useful for the analysis and interpretation of the dust extinction curves. Spectra in the blue-optical would be useful for tying the UV spectral types to the classical blue-optical spectral types, but is not required for this program. A multi-object capability would be ideal for this program given the relative compactness of our sources. The sensitivity is set by the need to obtain good signal-to-noise on a B5V star in our most distant galaxy (estimated at 50 to provide measurements of stellar features).

This program would generate datasets of photometry and spectroscopy that would be valuable in other areas of study. The photometric survey would produce A(V) and R(V) maps of all Local Group galaxies, with information on the full 3D structure of the ISM. Stellar populations studies would be possible with the same dataset, especially if coupled with similar data at longer wavelengths (e.g. PHAT-like). The large UV spectral library of hot, massive stars would provide for ample study of the early stages of stellar evolution over a range of metallicities and environments. These are just three of the many complimentary studies possible from the data obtained as part of this program.

RFI Details

Submitted in response to the Request for Information (RFI) for the "Science Objectives and Requirements for the Next NASA UV/Visible Astrophysics Mission Concepts" on 10 Aug 2012. Karl Gordon is the point of contact for this proposal. He is an Associate Astronomer at Space Telescope Science Institute. He is interested in participating in a workshop on this topic.

References

Bianchi, L., et al. 1996, ApJ, 471, 203

Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245

Clayton, G. C., Gordon, K. D., & Wolff, M. J. 2000, ApJS, 129, 147

Clayton, G. C., et al. 2003, ApJ, 588, 871

Draine, B. T. & Li, A. 2007, ApJ, 657, 810

Fitzpatrick, E. L. 1999, PASP, 111, 63

Fitzpatrick, E. L. & Massa, D. 2007, ApJ, 663, 320

Gordon, K. D. & Clayton, G. C. 1998, ApJ, 500, 816

Gordon, K. D., et al. 2003, ApJ, 594, 279

Maíz Apellániz, J. & Rubio, M. 2012, A&A, 541, A54

Massa, D., Savage, B. D., & Fitzpatrick, E. L. 1983, ApJ, 266, 662

Misselt, K. A., Clayton, G. C., & Gordon, K. D. 1999, ApJ, 515, 128

Smith Neubig, M. M. & Bruhweiler, F. C. 1997, AJ, 114, 1951

Valencic, L. A., Clayton, G. C., & Gordon, K. D. 2004, ApJ, 616, 912

Valencic, L. A., et al. 2003, ApJ, 598, 369

Weingartner, J. C. & Draine, B. T. 2001, ApJ, 548, 296

Zubko, V., Dwek, E., & Arendt, R. G. 2004, ApJS, 152, 211