Measuring Interstellar Extinction

1. Historical and Scientific Background

The interstellar extinction of starlight is the most indicative phenomenon revealing the presence of diffuse dark matter in the Galaxy. The first documented observation of extinction effects, appearing in the form of dark regions, is that of Sir William Herschel who in 1784 observed a section of the sky containing no stars. The nature of such dark spots remained a mystery through many years, even as late as the publication of the famous *Atlas of the Selected Regions of the Milky Way* by E. Barnard in 1919 and 1927, which proved the existence of many dark regions in the sky differing in size (from a few degrees to only an arcminute) and shape (from almost circular to completely irregular). Astronomers of the 1920's and 1930's finally concluded that the "voids" observed in the stellar background are due to the presence of some irregularly distributed diffuse matter that causes *extinction*, preventing stellar photons from reaching the observer (Trumpler 1930a).

The extinction is the sum of two physical processes: absorption and scattering. Absorption is efficient for particles (i.e., ISM dust grains) with physical sizes a larger than the wavelength of the incident radiation λ. Scattering peaks in efficiency for $a \sim \lambda$. Because the number density of dust grains in the interstellar medium (ISM) is a steeply decreasing function of size, $n(a) \propto a^{-3.5}$, extinction is generally stronger at shorter wavelengths. Trumpler (1930b) demonstrated that extinction depends on wavelength approximately as λ^{-1}. More recently, it has been shown that even if the overall wavelength dependence of Trumpler's result is correct, the extinction law depends on location (e.g., Gordon et al. 2003). For example, ISM dust in the Milky Way galaxy has different extinction properties as a function of wavelength than do the Milky Way's satellites: the Small and Large Magellanic Clouds (Fig. 1).
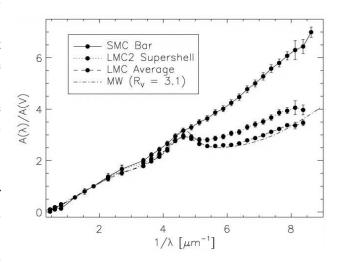

Fig. 1.— Comparison of the extinction laws in the Milky Way (MW), the Large Magellanic Clouds (LMC), and the Small Magellanic Cloud (SMC). Figure from Gordon et al. (2003).

The general increase in absorption toward shorter wavelengths gives rise to the effect of *reddening*. This can be easily gleaned from multi-wavelength images of the sky toward regions of interstellar dust (Fig. 2). The most common measure of reddening is the color excess

$$E_{B-V} = A_B - A_V = (B - V) - (B - V)_0, \tag{1}$$

where $(B - V)_0$ denotes the intrinsic value for the color index of the star under consideration. A_B and A_V are the total extinctions in the photometric B (450 nm) and V (550 nm) bands, such that

$$V = V_0 + A_V, \qquad B = B_0 + A_B, \tag{2}$$

where V_0 and B_0 are the intrinsic values for the magnitudes of the star. As follows from the above formula, the color excess may be determined even when the total extinction is not known in any of the photometric bands.
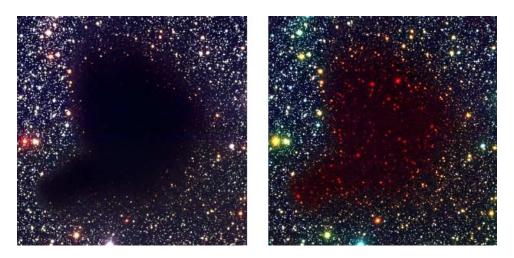

Fig. 2.— Tri-color composite images of the Barnard 68 dust cloud: BVI (450 nm, 550 nm, 800 nm; **left**) and BIK (550 nm, 800 nm, 2200 nm; **right**) (*Figure credit: European Southern Observatory.*)

Table 1 lists the wavelength dependence of extinction based on the empirically derived Milky Way extinction law. The total extinction can then be determined from the color excess (Eq, 1) as follows

$$E_{B-V} = A_B - A_V = \left(\frac{A_B}{A_V} - 1\right) A_V = 0.324 A_V \Rightarrow A_V = 3.086 E_{B-V} \approx 3.1 E_{B-V}. \quad (3)$$

The ratio A_V/E_{B-V} is sometimes denoted as R_V.

Table 1: Wavelength Dependence of Milky Way Extinction

Band	λ [nm]	A_λ/A_V
U	360	1.531
B	450	1.324
V	550	1
R	660	0.748
I	800	0.482
J	1250	0.282
H	1650	0.175
K	2200	0.112
L	3500	0.058
M	4800	0.023

The measurements of interstellar reddening is an important tool for estimating extinction toward homogeneous stellar populations (e.g., galactic open or globular clusters), and hence correcting their color-magnitude diagrams for the effect of extinction (Fig. 3). In turn, once the non-extincted color-magnitude diagram has been obtained, the distance and the age of the stellar population can be estimated through main sequence and model fitting. The interstellar extinction A_V can also be converted directly to distance r through the following approximate relations for extinction as a function of galactic latitude b (in degrees):

$$A_V \approx 2\frac{r}{\text{kpc}}\,\text{mag}, \qquad b < 2°, \qquad (4)$$

$$A_V \approx \frac{0.18}{\sin b}\,\text{mag}, \qquad b > 10°. \qquad (5)$$
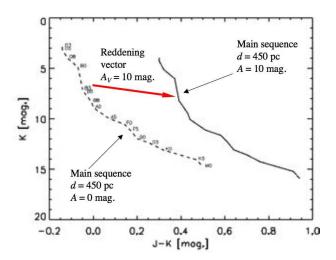

Fig. 3.— The effect of $A_V = 10$ mag of interstellar reddening on the near-infrared color-magnitude diagram of a dust-obscured stellar population at 450 pc.

Reddening can be estimated in a distance-independent fashion from a color-color diagram of a population of stars, by comparing it to the locus of unreddened main sequence stars. The result is most clearly seen in the color-color diagram of a dust-obscured young (<500 Myr) open cluster with massive, early-type (B and A) stars, which have near-zero $B - V$, $V - R$, and $R - I$ colors. Globular clusters tend to be much older (>10,000 Myr) populations of stars, in which all early-type stars have long evolved off the main sequence.

2. Experiment Goals and Plan

The experiment aims to measure the amount of reddening E_{B-V} and extinction A_V toward a galactic open cluster from an optical color-color diagram.

Actions marked with *"PHY 517"* are required only of graduate students. All students are responsible for all other actions.

2.1. Experiment Goals

- obtain absolutely calibrated optical photometry of a reddened open cluster;

- construct a color-color diagram and from that determine reddening, and extinction;

- determine the distance to the cluster through main sequence fitting; compare that distance to what you would infer from the galactic extinction–distance relation;

- *PHY 517:* fit theoretical isochrones to the extinction-corrected color-magnitude diagram and determine the age of the open cluster.

2.2. Experiment Plan

1. Choose which open or globular cluster you will observe. Good targets will be $\sim$50–500 Myr-old open clusters close to the galactic plane. The age range ensures the presence of B and/or A-type stars with near-zero magnitude colors, while the location ensures high amounts of interstellar extinction. Of course, you may well not have any information on the age of a newly-discovered open cluster, but choosing an open, rather than a globular cluster will generally limit you to ages <1 Gyr.

2. Plan to take exposures in at least three broad-band filters, and make sure that you will expose deep enough (through repeated exposures) to probe most of the main sequence, especially if your cluster is distant (e.g., has a small apparent angular size) and obscured. Which is the filter most sensitive to extinction?

3. Since this experiment requires absolute calibration of your apparent photometry, you will need to choose one or several photometric standards near (within $\sim$5° of) your science field. You will observe the standards at regular intervals during the night in each of the filters to monitor changes in atmospheric transmission. For this to give proper calibration at all, your night needs to be "photometric": no clouds with stable seeing. You can monitor both conditions in real time.

   References for $UBVRI$ photometric standards: Landolt (1983, $7 < V < 13$ mag; $-75° < \delta < +30°$), Landolt (1992, 2009, $8.9 < V < 16.3$ mag; mostly $-10° < \delta < +10°$), Landolt & Uomoto (2007, $10 < V < 16$ mag; $-52° < \delta < 70°$).

4. Print $60' \times 60'$ finding charts for your science target and for your selected standard stars.

5. Acquaint yourself with how to operate the Mt. Stony Brook 14-inch telescope, and the SBIG STL-1001E CCD camera.

6. Plan to arrive at the telescope at least 2 hours before the start of your observations. Assemble the spectrograph and the CCD, perform an initial focusing, mount them on the telescope, and finalize focusing on a bright star.

7. Start by observing your chosen 1–3 standard stars in all filters in which you will take science observations. Do no spend more than $\sim$5 min on your calibration observations. However, make sure that you have a sufficiently high number of counts (at least 5000 above background) in your standard star to reduce the random error in the calibration.

8. Proceed to taking images of your science target in the chosen filters. Return to your standard stars every $\sim$30 min or when the airmass ($\sec(\mathrm{zenith\,angle})$) changes by 0.2.

9. Autoguiding is not essential for these observations, as long as you perform occasional corrections to the telescope pointing, such that the recorded field around your science target stays mostly the same.

10. Take calibration exposures, darks and flats, if you have not done so already. You should obtain high- and low-illumination (i.e., long and short exposure times) dome flats in each of the filters that you used. Make sure that the dome lights are turned on for you flats, and to also obtain darks with the same exposure time as the dome flats.

11. Shut down all equipment and transfer the recorded data onto a memory stick.

3. Data Acquisition

Make sure that you obtain sets of "dark" frames with exposure durations corresponding to those of all of your calibration and science images. Darks can be obtained automatically by the CCD after each exposure, with the saved image file being the difference between the "light" and the dark exposure, or can be obtained separately at the end of your observations. Taking darks immediately after each exposure effectively doubles the time to get any single exposure, but may be convenient for short observations. CCDSoft also allows you to take darks only after every N-th exposure in a series. For long ($\gtrsim$30 sec) exposures you may find it more practical to take a single set of darks at the end of the night.

Make sure to keep a good observing log in your lab book. In particular, proper records of target names, exposure numbers, start times, durations, and sky conditions are essential. Keep a current record of, or infer at a later time for each exposure, the elevation of your target above the horizon. You will find this information useful at a later time in judging the quality of your data.

4. Data Reduction

Briefly, you will:

1. create the appropriate calibration frames: master dark (if necessary), flat field, and bad pixel mask;

2. reduce each individual image with the calibration frames: i.e., subtract dark (if not already done), divide by flat, correct for bad pixels;

3. measure the photometry of each of your standard stars, and plot it as a function of airmass in each filter: this is called an "airmass curve";

4. identify all cluster member stars in your images through comparisons with published memberships in the literature. Because the CCD does not save coordinate and pointing information in the FITS image headers, you may find the `astrometry.net` service helpful for solving for the coordinates of your image;

5. for each sequence of data in between standard star observations, align and median-combine the images to get a deeper exposure;

6. measure the fluxes of the cluster members in each of the median-combined exposures and in each filter, correct them for the airmass of the observation from the airmass curve, and calibrate them with respect to the fluxes of the standard stars to so obtain magnitudes.

All of the data reduction is done in IDL. ATV could be used for inspection of individual images, but it would be highly impractical for photometry on a large number of stars.

The relevant IDL programs are either part of the IDL language,[1] or are available as an add-on from the Astronomy User's Library[2]. You will further have to write simple IDL scripts to string these programs together for automated execution.

Some notes on a few of the steps outlined above follow.

4.1. Creating Calibration Frames

Useful IDL tasks:
MEDIAN: part of IDL
READCOL, READFITS, WRITEFITS: Astronomy User's Library
ATV, FIXPIX, STRC: independently contributed.[3]

To create a master dark for a given exposure time, median-combine all dark images taken at this exposure time. This high signal-to-noise dark can then be subtracted from all images of the same exposure time.

To create a master flat, subtract a (master) dark from all flat frames, and median combine them for each filter and exposure time. Normalize the median-combined high-signal flat to unity by dividing it by its mode. This is your master flat, and it is different for each filter. Each science exposure now needs to be divided by its master flat.

To create a bad-pixel mask, divide the median-combined (non-normalized) high-signal flat by the median-combine low-signal flat. Ideally, the ratio would identically equal the ratio of exposure times in each pixel. However, not all pixels respond sufficiently linearly with flux. Select pixels that are bad, e.g., with responsivity $>5\sigma$ away from the mean, and create a binary bad-pixel mask of, e.g., 0 for bad pixels and 1 for good pixels. The bad pixel mask has the same dimension as all images, and can be applied with the FIXPIX procedure[4].

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[1]For an alphabetical listing of IDL routines, see, e.g., http://www.physics.nyu.edu/grierlab/idl_html_help/idl_alph.html

[2]http://idlastro.gsfc.nasa.gov/contents.html

[3]For FIXPIX and STRC, see files fixpix.pro and strc.pro at http://www.astro.ucla.edu/~mperrin/IDL/sources/

[4]http://www.astro.ucla.edu/~mperrin/IDL/sources/fixpix.pro

4.2. Cluster Membership Identification

Obtain a coordinate solution for your median-combined images with the help of `astrometry.net`. Then select known cluster members through comparisons with published stellar members in the literature.

4.3. Photometric measurements

Useful IDL tasks:
FIND, APER, READCOL, READFITS: Astronomy User's Library
ATV: independently contributed

Measure the fluxes of all standard stars and of all open cluster members in the few median-combined stacks of science images created from each sequence of raw science images. Derive the airmass curve—change in flux as a function of airmass—for each filter by taking the data from all standard stars together.

Measure the fluxes of all open cluster members, and apply to them the airmass curve correction. Also convert aperture fluxes to magnitudes by using teh known magnitudes of the standard stars.

5. Analysis and Discussion

5.1. Inferring the Extinction from a Color-Color Diagram

Plot a color-color diagram, e.g., $B - V$ vs. $V - I$ for all stars, and compare the locus of the bluest cluster members to the locus of the bluest main sequence stars; obtain the latter from Cox (2000). The vector connecting the centers of the two loci represents the reddening in each of the colors. These can now be converted to magnitudes of visual extinction A_V through Eq. 3 and Table 1. Check for consistency between the independent extinction estimates from the two colors.

5.2. Inferring the Distance

Create an unextincted color-magnitude diagram of the open cluster, e.g., V vs. $B - V$, and compare it to the main sequence locus (e.g., Cox 2000, from).

Shift the color-magnitude relation of the cluster up or down until it fits the main sequence. The amount of the shift is the distance module of the cluster. Convert that to distance in pc, and compare to what you would expect if you had simply assumed the galactic extinction law in Eq. 5.

5.3. Estimating the Age of the Cluster (*PHY 517*)

Once you have obtained an unextincted color-magnitude diagram and you know the distance, fit to your data a range of theoretical isochrones, e.g., from the Padova database of stellar evolu-

tionary models[5].

5.4. Discussion (*PHY 517*)

How accurate of a distance measure to a cluster can be obtained through the two approaches: galactic extinction relation and main sequence fitting? How good is your fit for the age of the cluster, as expressed by its reduced χ^2 value?

When using the color-color diagram of the cluster for estimating its reddening with respect to unreddened main sequence stars, you may have assumed certain age limits for the cluster to infer the colors of its bluest members. Are the main sequence lifetimes of these bluest stars consistent with your age estimate? How might your estimates improve if you iterate on your approach, using the age obtained from the first follow-through of the process as an input to the second iteration?

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[5]http://stev.oapd.inaf.it/cmd

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