Spring 2009 **Astro 530: Galaxies**

Problem Set #2
Due Thursday January 29, 2009

2. [Adopted from Sandy Faber's graduate Galaxies class] This problem explores the effects of normal dust on the light and color of galaxies for various distributions of the dust along the line-of-sight.

a) The standard reddening curve, illustrated in Lecture 2 has the property that:

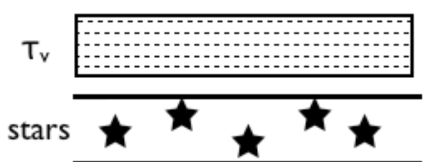
$$A_B = 1.31\ A_V \qquad \text{and} \qquad A_U = 1.54\ A_V$$

Show that these correspond the the familiar values:

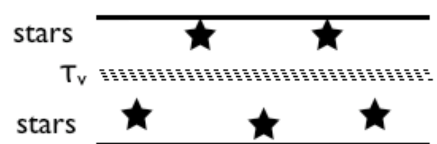
$$R_V = A_V/E(B-V) = 3.1 \qquad \text{and} \qquad E(U-B)\ /\ E(B-V) = 0.72$$

b) In each case below, assume that the total optical depth of the dust layer is τ_v and that the ratios of the absorptions in the different colors are given above. The stars and dust are distributed in infinite plane-parallel layers, with the observer towards the top of the page. In Case A, the dust is entirely in front of the stars. In Case B, it is located entirely in the mid-plane of the stellar distribution. In Case C, the dust and stars are well mixed. Assume that, in the absence of dust, the specific intensity of light emerging perpendicular to the stellar layer is I_o in all wavelength bands.

CASE A



CASE B



CASE C

For each case, use the equation of radiative transfer to derive expressions for the effective absorptions A_V, A_B and A_U in magnitudes. Then use these to derive corresponding expressions for R_V and $E(U-B)/E(B-V)$ in each case.

c) Take the limits $\tau_V = 0$ and $\tau_V = \infty$ and evaluate R_V and $E(U-B)/E(B-V)$ numerically. Watch out while taking limits for $\tau_V = 0$. Justify that each limit makes sense intuitively.

COMMENT #1: What have you learned in this problem? Case A corresponds to the familiar one in which the dust lies entirely between the source and the observer (e.g.. Schlegel, Finkbeiner & Davis 1998). You should have recovered the standard values of R_V and E(U-B)/E(B-V) for both limits of the extinction. Case B corresponds roughly to the face-on view of a spiral disk with a thin mid-plane dust layer. Case C corresponds to a homogeneous mixture of stars and dust long the line of sight. Cases B and C illustrate the fact that the familiar values of R_V and E(B-V) are not valid for galactic light seen by outside observers, even for normal dust. (Nevertheless, one sees these de-reddening 'corrections' blindly applied in the literature).

COMMENT #2: A further complication for real galaxies is the fact that dust has non-zero albedo and partially scatters light rather than absorbing it. Thus absorption can actually produce EXCESS light along certain lines of sight. This acts to brighten spirals when they are seen face-on. Whether galaxies are dimmed or brightened by dust (or reddened) is a sensitive function of the dust grain albedos, how the dust is distributed with respect to the stars and the orientation of the system with respect to the observer. This is complicated, but possible to model using, e.g.. a Monte Carlo radiative transfer code. See Jonsson et al 2006 (MNRAS, 372, 2), and check out realistic-looking simulated galaxies using this code (SUNRISE) at:

http://www.ucolick.org/~patrik/sunrise/

3. Most extragalactic studies assume that the reddening to a system is due entirely to foreground dust in the Milky Way. Under this assumption, the amount of reddening can be measured by comparing the colors of stars to that predicted from theoretical isochrone tracks. The most straightforward case is measuring the reddening to a resolved single stellar population (e.g. a nearby globular or open star cluster).

SDSS data for the Milky Way open cluster M67 is available on the class website. This is one of the oldest known open star clusters in the Milky Way, with an age and metallically of roughly 4 Gyr and [Fe/H] = -0.1 dex. Download the appropriate theoretical isochrone from Aaron Dotter's website (linked on the class website, under Class Tools):

http://stellar.dartmouth.edu/~models/isolf.html

a) Plot a color-magnitude diagram (g-r) vs. r for M67. Over-plot the theoretical isochrone. As a first guess, shift by hand the isochrone in the horizontal and vertical directions to match the data. Explain the following features in the data: (i) the S-shape of the main locust of points, (ii) the cloud of points blue-ward of main locust, and (iii) the shape of faint-end cut-off. Based on these features, design a rough scheme to isolate likely members of M67 (for example, using only stars with small error bars which lie close to the isochrone track).

b) Independent of what filters you observe in, reddening is usually quantified (and stated in the literature as) the color excess E(B-V). Measure the color excess E(B-V) for M67. First, plot a cleaned color-color diagram (g-r) vs. (r-i). Match the theoretical isochrone to the data, using the only free parameter E(B-V). Conversions to the SDSS filters (from Schlegel, Finkbeiner & Davis 1998, hereafter SFD98) are as follows:

$$A(g)/A(V) = 1.161 \quad \text{and} \quad A(r)/A(V) = 0.843$$

Fit for the quantity E(B-V) by minimizing the average distance of each data point to the isochrone. Describe your fitting method.

c) Measure the distance modulus $(m-M)_0$ to M67. First plot the color-magnitude diagram, correcting for the reddening, and then fit the theoretical isochrone vertically. Note that the subscript on the distance modulus means that this is the magnitude difference due to distance only (e.g. not including extinction). What is this distance in kpc?

d) If binary stars were present in this cluster, how would this affect your distance modulus and reddening? If M67 were not a true single stellar population, how would this affect your results? Is there a difference for a mixture of ages (at a single metallicity), versus a mixture of metallicities (at a single age)?

e) How does your distance result for M67 compare to literature values? How does your reddening result compare to that from SFD98 (available on the NASA Extragalactic Database (NED)) Describe how the SFD98 reddening value is measured and compare this to your method.

COMMENT: For more distant galaxies which cannot be resolved into individual stars, there are multiple degeneracies in determining age, metallicity, reddening and distance. In practice, reddening to extragalactic systems is assumed to be the SFD98 value and distance is determined via the galaxy's recessional velocity or other methods (Cepheids, surface brightness fluctuations, etc.). Age/metallicity is then determined by compare integrated colors to theoretical isochrones.