Problem 3 - Ay 216 Interstellar Medium, Spring 2008

Dust and HII Regions

1. Using Hydrogen Lines to Measure the Extinction

The dust towards HII regions can be determined by measuring the relative intensity of their recombination lines. For general background on dust and H II regions, consult Ch. 7 of the book by Osterbrock & Ferland.

Starting with the parameterization of the interstellar extinction curve by Cardelli, Clayton & Mathis (ApJ, 345 245 1989), plot A_λ/A_V as a function of $1/\lambda$ (λ in $\mu\mathrm{m}^{-1}$) for $R_V = 3.1$ and $R_V = 5.0$. You will need this curve to answer the following questions:

a) Find the ratios

$$A_{H\beta}/(A_{H\beta} - A_{H\alpha}),$$

$$A_{Br\alpha}/(A_{Br\gamma} - A_{Br\alpha}),$$

for both values of R_V, where $A_{H\alpha}$ is the extinction at the wavelength of Balmer α ($n = 3 \rightarrow 2$ and $A_{Br\alpha}$ is the extinction at the wavelength of Brackett α ($n = 5 \rightarrow 4$).

Use the rest wavelengths of the HI emission lines tabulated in the online NIST database (http://physics.nist.gov). Describe how you interpolated the extinction curve between the optical/infrared and UV/FUV empirical regimes considered by Cardelli et al.

b) Look up the intrinsic $I(H\alpha)/I(H\beta)$ and $I(Br\alpha)/I(Br\gamma)$ line ratios in Hummer & Storey (MNRAS, 224 801 1987) for Case B recombination for a low density HII region with $T_e = 10^4$ K.

c) By comparing observed line ratios to their Case B values, you can estimate the amount of extinction along the line of sight. Start by assuming that all of the extinction arises in a simple foreground screen, and derive an expression for A_V in terms of the observed and intrinsic emission-line ratios, $I(H\alpha)/I(H\beta)$ and $I(Br\alpha)/I(Br\gamma)$, for $R_V = 3.1$

d) Next consider a slab geometry in which the dust is uniformly mixed with the emission-line gas, rather than the dust being in front of the gas. Using the slab geometry, show that the solution of the equation of radiative transfer for the case of mixed gas and dust is.

$$I/I_0 = (1 - \exp(-\tau))/\tau.$$

For this case, derive formulae for A_V for the $I(H_\alpha)/I(H_\beta)$ and $I(Br\alpha)/I(Br\gamma)$ line ratios, again for $R_V = 3.1$.

e) Turning the problem around, make plots of the observed line ratios as a function of A_V in the range $0 < A_V/\mathrm{mag} < 30$ for each of the emission line ratios for both the screen and the slab geometries. Make separate plots for $I(H\alpha)/I(H\beta)$ and $I(Br\alpha)/I(Br\gamma)$.

f) Comment on the implications of your results for using Balmer and Brackett line intensity ratios to estimate the intrinsic extinction of dusty HII regions. In what circumstances do you expect that the slab geometry might be more relevant than the screen geometry?

g) Hydrogen recombination line ratios have been measured for the nuclear starburst region of M82 (Table 5, column 4 of Forster-Schreiber et al. ApJ, 552 544 2001). What is the extinction? Compare this with the extinction to individual star forming clusters in this galaxy measured by McCrady Graham & Gilbert (ApJ, 596 240 2003), and comment on the different approaches.

2. Circumstellar Dust

The Infrared Astronomy Satellite (IRAS) detected a significant excess at infrared wavelengths ($\lambda > 12$ μm) from the otherwise normal main-sequence A0V star Vega (Aumann et al. ApJ, 278, L23, 1984). The infrared excess is thought to be due to emission from circumstellar dust in thermal equilibrium with the stellar radiation from the central star, distributed in a shell or ring several tens to hundred AU in extent. Since then a large number of main-sequence stars have been found to have similar infrared excesses in the IRAS wavebands, and they are called Vega-like stars (Backman & Paresce in Protostars and Planets III, pp. 1253-1304, 1999).

Construct a model infrared spectrum of an optically thin shell of dust around an A star like Vega. First assume that the star radiates like a blackbody. Sub-mm mapping shows that dust in this system is present between radii of 80 and 120 AU. Consider grains only at 100 AU. Initially adopt a single grain size, e.g., 0.1 μm, and composition, e.g., Draine's "astronomical silicates". Calculate the equilibrium temperature of the grains using $Q_{\mathrm{abs}}(\lambda)$ computed from Mie theory or tabulated by Draine. Do not assume that the grains behave as blackbodies in the UV or IR. Compute the emergent spectrum for a single dust grain at the highest spectral resolution permitted by tabulated optical constants. Consider the spectrum in the 10-40 μm range, which is the band pass of the IRS spectrometer on the *Spitzer Space Telescope*. Results from *Spitzer* are now beginning to be published on debris disks (e.g., starting with Volume 154 of ApJ Supplements). How do your predictions stack up against these first reports?

Some Technical Aids

1. Bruce Draine maintains a web page of optical constants which are suitable for computing the UV/optical absorption properties of dust:

`http://www.astro.princeton.edu/~draine/dust/dust.diel.html \\`

Also see his review of interstellar dust (ARAA, 41 241 2003).

2. Additional high spectral resolution optical constants in the infrared for various candidate grain materials are given by Henning et al. (A&AS, 136 405 1999) and on line at:

`http://www.astro.uni-jena.de/Laboratory/Database/odata.html`

3. A collection of IDL Mie scattering codes can be found at:

`http://www-atm.physics.ox.ac.uk/group/mie/`