Physics 772
Problem Set #4

Heating the Interstellar Medium with Cosmic Rays

Keeping the interstellar medium at its observed temperature requires a power input of about $5 \times 10^{-33}$ watts/hydrogen atom, on the average, and is almost independent of density. It is still uncertain what mechanism provides this energy.

One popular candidate was ionization heating by cosmic rays. Use the proton spectrum shown in Figure 9.1 on page 271 of Longair, vol I (provided on back). The turnover at low energies (below $10^4$ MeV/nucleon) is caused by exclusion of low-energy cosmic rays from the inner solar system (where they are observed) by the solar magnetic field. Assume a straight-line extrapolation of the high energy part to get the interstellar spectrum. Write an equation for this $I(E)$ line. Note the units carefully.

Calculate the heat input to a single hydrogen atom from this cosmic ray flux between some $E_{\text{min}}$ and $E_{\text{max}}$. As an approximation, you can use the non-relativistic formula below 1000 MeV, and the fully-relativistic form above this energy. Note that the formula is for energy loss by a proton, and we want energy input to one target atom. You can easily turn it around to use this way. If it helps, think of some large density of hydrogen atoms ($N/m^3$) and calculate the energy loss of a proton of energy $E$ going through this, then add that for all the particles between $E_{\text{min}}$ and $E_{\text{max}}$ in the cosmic ray spectrum/second that pass through this cubic meter in $1^5$ (don't forget the $4\pi$). Then divide by $N$ to get the power/Hydrogen atom.

Note that in this course we seldom try to do numerical calculations exactly. If integrals look hard, take out some slowly-varying part and approximate it with a constant. (This is always a good idea on a first cut anyhow -- you're less likely to make a mistake and will have a good idea what sizes the numbers are.) You may need to iterate once to get reasonably close to the right value, but you'll have a better feeling for the magnitudes involved.

Is the relativistic part of the spectrum important?
What $E_{\text{min}}$ is required to get the total heating?
What is the fractional contribution of He as shown in Figure 9.1?

The prime candidate for heating is now photoelectric effect on grains, or possibly dissipation of turbulence. The interstellar proton spectrum is not thought to continue to such low energies. Cosmic ray heating is probably important and may dominate in molecular clouds.
Figure 9.1. The differential energy spectra of cosmic rays as measured at the Earth from observations made from above the Earth's atmosphere. The spectra for hydrogen, helium, carbon and iron are shown. The solid line shows the unmodulated spectrum for hydrogen, i.e. the effects of propagation through the interplanetary medium upon the energy spectra of the particles have been eliminated using a model for the modulation process. The flux of helium nuclei below about 60 MeV nucleon$^{-1}$ is due to an additional flux of these particles which is known as the anomalous $^4$He component. (From J. A. Simpson (1983). Ann. Rev. Nucl. Part. Sci., 33, 330).