IMPACT 2 …ON ASTROPHYSICS: The Sun as a ball of perfect gas

The kinetic model of gases is valid when the size of the particles is negligible compared with their mean free path. It may seem absurd, therefore, to expect the kinetic model and, as a consequence, the perfect gas law, to be applicable to the dense matter of stellar interiors. In the Sun, for instance, the density at its centre is 1.50 times that of liquid water and comparable to that of water about half way to its surface. However, the state of matter in the Sun is that of a *plasma*, in which the electrons have been stripped from the atoms of hydrogen and helium that make up the bulk of the matter of stars. As a result, the particles making up the plasma have diameters comparable to those of nuclei, or about 10 fm. Therefore, a mean free path of only 0.1 pm satisfies the criterion for the validity of the kinetic theory and the perfect gas law. The relation $pV = nRT$ can therefore be used as the equation of state for the stellar interior. Although the Coulombic interaction between charged particles is strong, at the high temperatures of stellar interiors the kinetic energy of the charged particles is very much greater and so a 'kinetic-energy only' is a tolerable approximation.

As for any perfect gas, the pressure in the interior of the Sun is related to the mass density, $\rho = m/V$, by $p = \rho RT/M$. Atoms are stripped of their electrons in the interior of stars so, if it is supposed that the interior consists of ionized hydrogen atoms, the mean molar mass is one-half the molar mass of hydrogen, or 0.5 g mol^{-1} (the mean of the molar mass of H^+ and e^-, the latter being virtually zero). Half way to the centre of the Sun, the temperature is 3.6 MK and the mass density is 1.20 g cm^{-3} so the pressure there works out as 72 TPa, or about 720 million atmospheres.

Because the total kinetic energy of the particles is $E_k = \frac{1}{2}Nmv_{rms}^2$, $p = \frac{2}{3}E_k/V$. That is, the pressure of the plasma is related to the *kinetic energy density*, $\rho_k = E_k/V$, the kinetic energy of the molecules in a region divided by the volume of the region, by $p = \frac{2}{3}\rho_k$. It follows that the kinetic energy density half way to the centre of the Sun is about 0.11 GJ cm^{-3}. In contrast, on a warm day (25 °C) on Earth, the (translational) kinetic energy density of the atmosphere is only 0.15 J cm^{-3}.