

## STRESS-ENERGY TENSOR - RELATIVISTIC PERFECT FLUID

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We saw in the last post that even at the centre of the sun, the energy of the protons and electrons in the plasma is still non-relativistic and the pressure is still a very small fraction of the energy density. An interesting question is: how fast do particles need to move in a perfect fluid in order for the pressure to become significant in the stress-energy tensor?

Let's say we want the pressure to be 1% of the energy density, as measured in the fluid's rest frame. The energy density of a plasma containing  $N$  particles, each of mass  $m$  in a volume  $V$  is

$$\rho_0 = \gamma m \frac{N}{V} \quad (1)$$

If we take a simplified case where all particles are moving at the same speed  $v$ , but in random directions, then the four-momentum is

$$\mathbf{p} = \gamma m [1, v^x, v^y, v^z] \quad (2)$$

$$v = \sqrt{(v^x)^2 + (v^y)^2 + (v^z)^2} \quad (3)$$

When deriving the stress-energy tensor, we found that the pressure due to a particle moving with an  $x$  component of speed  $v^x$  could be written as

$$\Delta P = \frac{(p^x)^2}{p^t V} = \frac{(\gamma m v^x)^2}{\gamma m V} = \gamma m \frac{(v^x)^2}{V} \quad (4)$$

With  $N$  particles, the total pressure is (assuming that  $v^x$  averages out to the same value for all particles):

$$P = \gamma m N \frac{(v^x)^2}{V} \quad (5)$$

Further, we can assume that on average  $v^x = v^y = v^z$  so we can write this as

$$P = \frac{\gamma m N v^2}{3} \quad (6)$$

If the pressure is to be 1% of the energy density, then

$$\frac{\gamma m N v^2}{V} \frac{1}{3} = 0.01 \gamma m \frac{N}{V} \quad (7)$$

$$v = \sqrt{0.03} = 0.173 \quad (8)$$

Thus the particles need to be moving at a significant fraction of the speed of light in order for the pressure to be significant.