

STRESS-ENERGY TENSOR: RELATIVISTIC PERFECT FLUID

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Reference: Moore, Thomas A., *A General Relativity Workbook*, University Science Books (2013) - Chapter 20; Problem 20.2.

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

$$(0.1) \quad \rho_0 = \gamma m \frac{N}{V}$$

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

$$(0.2) \quad \mathbf{p} = \gamma m [1, v^x, v^y, v^z]$$

$$(0.3) \quad v = \sqrt{(v^x)^2 + (v^y)^2 + (v^z)^2}$$

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

$$(0.4) \quad \Delta P = \frac{(p^x)^2}{p^t V} = \frac{(\gamma m v^x)^2}{\gamma m V} = \gamma m \frac{(v^x)^2}{V}$$

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

$$(0.5) \quad P = \gamma m N \frac{(v^x)^2}{V}$$

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

$$(0.6) \quad P = \frac{\gamma m N v^2}{V} \frac{1}{3}$$

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

$$(0.7) \quad \frac{\gamma m N v^2}{V} \frac{1}{3} = 0.01 \gamma m \frac{N}{V}$$

$$(0.8) \quad v = \sqrt{0.03} = 0.173$$

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