

# Astro 507; Problem Set 2

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## ***1. Heat Capacities***

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The definition of heat capacity gives that

$$C \equiv \frac{dQ}{dT} \quad (1)$$

$C_P$  and  $C_V$  are  $C$  but with the pressure,  $P$ , and volume,  $V$ , each held constant respectively. Applying the first law of thermodynamics, this gives

$$C_V = \frac{dU}{dT}, \quad C_P = \frac{dU}{dT} + P \frac{dV}{dT} \quad (2)$$

Therefore the difference of the two is found as follows (applying the ideal gas law).

$$C_P - C_V = P \frac{dV}{dT} \quad (3)$$

$$= P \frac{d}{dT} \left( \frac{Nk_B T}{P} \right) \quad (4)$$

$$= P \left( \frac{Nk_B}{P} \right) \quad (5)$$

$$\boxed{C_P - C_V = Nk_B} \quad (6)$$

Now we can additionally find the ratio of the two

$$\frac{C_P}{C_V} = \frac{\frac{dU}{dT} + P \frac{dV}{dT}}{\frac{dU}{dT}} \quad (7)$$

$$= 1 + P \frac{dV}{dT} \frac{dT}{dU} \quad (8)$$

$$= 1 + P \frac{dV}{dU} \quad (9)$$

TODO: not sure where to go now, do we know that  $U$  is?

## 2. The Fastest Electron

We are given the following information:

$$V = (40 \text{ kpc})^3, \quad n = 0.01 \text{ cm}^{-3}, \quad T = 10^6 \text{ K} \quad (10)$$

This means that the total number of particles in this volume is approximately

$$N = nV = 1.88 \times 10^{67} \quad (11)$$

I think that this means that the fastest particle would have a probability of  $1/N$ . We of course know that the Maxwell-Boltzmann distribution is

$$f(v) = \left( \frac{m}{2\pi k_B T} \right)^{3/2} 4\pi v^2 \exp \left( -\frac{mv^2}{2k_B T} \right) \quad (12)$$

In order to find the maximum velocity we can set the following integral equal to  $1/N$  since we need to find the velocity above which the probability of finding a particle is  $1/N$  (such that we expect to find a single particle).

$$\frac{1}{N} = \int_{v_{\max}}^{\infty} f(v) dv \quad (13)$$

$$= \int_{v_{\max}}^{\infty} dv \left( \frac{m}{2\pi k_B T} \right)^{3/2} 4\pi v^2 \exp \left( -\frac{mv^2}{2k_B T} \right) \quad (14)$$

$$= \sqrt{\frac{2}{\pi}} \int_{v_{\max}}^{\infty} dv \left( \frac{m}{2k_B T} \right)^{3/2} v^2 \exp \left( -\frac{mv^2}{2k_B T} \right) \quad (15)$$

$$= \sqrt{\frac{2}{\pi}} \int_{v_{\max}}^{\infty} dv A^{3/2} v^2 \exp(-Av^2) \quad (16)$$

$$\approx \sqrt{\frac{2}{\pi}} \cdot \frac{\sqrt{A}}{2} v_{\max} \exp(-Av_{\max}^2) \quad (\text{apply hint})$$

$$\frac{1}{N} \approx \sqrt{\frac{A}{2\pi}} v_{\max} \exp(-Av_{\max}^2) \quad (17)$$

At this point I wasn't entirely sure how to solve this so I plugged the whole lot into mathematica (using the values for  $N$  and  $T$  above plus assuming  $m = m_e$ ). After also asserting that  $v_{\max}$  is large, this gives

$$\boxed{v_{\max} = 6.9 \times 10^7 \text{ m s}^{-1}} \quad (18)$$

Given that  $0.99c \approx 3 \times 10^8$ ,  $v_{\max}$  is approximately 23% of the speed of cosmic rays. This implies to me that cosmic rays **cannot** be thermal in origin.

### 3. Atmospheric Escape

#### 3a. Compute number density

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We know that the mean free path is defined as

$$\lambda_{\text{esc}} \equiv \frac{1}{n_{\text{esc}} \sigma}, \quad (19)$$

thus we can simply set this equal to the scale height and solve for the number density.

$$\lambda_{\text{esc}} = H \quad (20)$$

$$\frac{1}{n_{\text{esc}} \sigma} = \frac{k_B T}{mg} \quad (21)$$

$$\boxed{n_{\text{esc}} = \frac{mg}{\sigma k_B T}} \quad (22)$$

#### 3b. Particle flux expression

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Integration time! Basically just applying the double angle rule and doing some integrals.

$$\phi(v) dv = \frac{f(v)}{4\pi} dv \int_0^{2\pi} d\phi \int_0^{\pi/2} v \cos \theta \sin \theta d\theta \quad (23)$$

$$= \frac{vf(v)}{4\pi} dv \int_0^{2\pi} d\phi \frac{1}{2} \int_0^{\pi/2} \sin(2\theta) d\theta \quad (24)$$

$$= -\frac{vf(v)}{4\pi} dv \int_0^{2\pi} d\phi - \frac{1}{4} [\cos(2\theta)]_0^{\pi/2} \quad (25)$$

$$= -\frac{vf(v)}{4\pi} dv \int_0^{2\pi} d\phi - \frac{1}{4} \cdot (-1 - 1) \quad (26)$$

$$= \frac{vf(v)}{8\pi} dv \int_0^{2\pi} d\phi \quad (27)$$

$$\boxed{\phi(v) dv = \frac{vf(v)}{4} dv} \quad (28)$$

#### 3c. Total particle flux

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Right, let's see if I can remember how to do integrals! Let's start by performing a substitution.

$$\phi = \int_{v_{\text{esc}}}^{\infty} \phi(v) dv \quad (29)$$

$$= \frac{1}{4} \int_{v_{\text{esc}}}^{\infty} vf(v) dv \quad (30)$$

$$= \sqrt{\frac{1}{8\pi}} \int_{v_{\text{esc}}}^{\infty} \left( \frac{m}{2k_B T} \right)^{3/2} v^3 \exp \left( -\frac{mv^2}{2k_B T} \right) dv \quad (31)$$

$$= \sqrt{\frac{1}{8\pi}} \int_{v_{\text{esc}}}^{\infty} A^{3/2} v^3 \exp(-Av^2) dv \quad (32)$$

$$u = v^2, \quad \frac{du}{dv} = 2v \quad (33)$$

$$\phi = \sqrt{\frac{1}{8\pi}} \int_{v_{\text{esc}}^2}^{\infty} A^{3/2} v^3 \exp(-Av^2) \frac{du}{2v} \quad (34)$$

$$= \sqrt{\frac{1}{8\pi}} \int_{v_{\text{esc}}^2}^{\infty} \frac{1}{2} A^{3/2} u \exp(-Au) du \quad (35)$$

$$= \sqrt{\frac{A^3}{32\pi}} \int_{v_{\text{esc}}^2}^{\infty} u \exp(-Au) du \quad (36)$$

Okay let's pause for a second. That covers the substitution part, now we need to do integration by parts. Since I'm already using  $u$  let's call the two variables in integration by parts  $a$  and  $b$  such that

$$\int a db = ab - \int b da \quad (37)$$

In our case, we have that

$$a = u, \quad db = \exp(-Au) \quad (38)$$

and thus we can also write that

$$da = 1, \quad b = -\frac{1}{A} \exp(-Au) \quad (39)$$

So now putting that all together, we can write that the integral in full is

$$= \left[ u \cdot -\frac{1}{A} \exp(-Au) \right]_{v_{\text{esc}}^2}^{\infty} - \int_{v_{\text{esc}}^2}^{\infty} -\frac{1}{A} \exp(-Au) du \quad (40)$$

$$= \left[ -\frac{u}{A} \exp(-Au) \right]_{v_{\text{esc}}^2}^{\infty} + \frac{1}{A} \int_{v_{\text{esc}}^2}^{\infty} \exp(-Au) du \quad (41)$$

$$= \left( 0 + \frac{v_{\text{esc}}^2}{A} \exp(-Av_{\text{esc}}^2) \right) - \left[ \frac{\exp(-Au)}{A^2} \right]_{v_{\text{esc}}^2}^{\infty} \quad (42)$$

$$= \frac{v_{\text{esc}}^2}{A} \exp(-Av_{\text{esc}}^2) + \frac{\exp(-Av_{\text{esc}}^2)}{A^2} \quad (43)$$

Okay phew, we made it. Now let's go and plug that back in!

$$\phi = \sqrt{\frac{A^3}{32\pi}} \left( \frac{v_{\text{esc}}^2}{A} \exp(-Av_{\text{esc}}^2) + \frac{\exp(-Av_{\text{esc}}^2)}{A^2} \right) \quad (44)$$

$$= \frac{(1 + Av_{\text{esc}}^2) e^{-Av_{\text{esc}}^2}}{\sqrt{32\pi A}} \quad (45)$$

Now let's put this into the format that you asked for. My constant  $A$  is related to  $v_s$  as  $A = v_s^{-2}$  and thus we can write that  $Av_{\text{esc}}^2 = \lambda_{\text{esc}}$ . Additionally, we want this in terms of the total number of particles and so we multiply by the number density.

$$\boxed{\phi = \frac{n_{\text{esc}} v_s (1 + \lambda_{\text{esc}}) e^{-\lambda_{\text{esc}}}}{\sqrt{32\pi}}} \quad (46)$$

### 3d. Earth Hydrogen Loss

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Let's just quickly write down the constants that we've been given:

$$m \approx 2 \text{ amu} = 3.32 \times 10^{-27} \text{ kg}, \quad T = 1000 \text{ K}, \quad \sigma = \pi \text{ \AA}^2 = \pi \times 10^{-20} \text{ m}^2 \quad (47)$$

where the mass has come from them being hydrogen molecules. Now let's evaluate  $\lambda_{\text{esc}}, n_{\text{esc}}, v_s$  so that we can find  $\phi$ .

$$v_{\text{esc}} = 11200 \text{ m s}^{-1} \quad (48)$$

$$n_{\text{esc}} = \frac{m_{\text{H}_2} \cdot g}{\sigma k_B T} = \frac{3.35 \times 10^{-27} \text{ kg} \cdot 10 \text{ m s}^{-2}}{\pi \times 10^{-20} \text{ m}^2 \cdot 1.38 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1} \cdot 1000 \text{ K}} = 7.66 \times 10^{13} \text{ m}^{-3} \quad (49)$$

$$v_s = \sqrt{\frac{2k_B T}{m_{\text{H}_2}}} = \sqrt{\frac{2 \cdot 1.38 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1} \cdot 1000 \text{ K}}{3.35 \times 10^{-27} \text{ kg}}} = 2883 \text{ m s}^{-1} \quad (50)$$

$$\lambda_{\text{esc}} = \left( \frac{11200}{2883} \right)^2 = 15.1 \quad (51)$$

Cool, now it's time to just plug those numbers in to find about  $\phi$ .

$$\phi_{\text{H}_2} = 9.91 \times 10^{10} \text{ m}^{-2} \text{ s}^{-1} \quad (52)$$

Finally, we need to multiply this by the area through which the particles move. Since we are given that  $H \ll R$ , we can say the surface at this height is essentially the same as the surface area of the Earth.

$$\mathcal{R}_{\text{H}_2} = \phi \cdot 4\pi R_{\oplus}^2 \quad (53)$$

$$= 9.91 \times 10^{10} \text{ m}^{-2} \text{ s}^{-1} \cdot 4\pi (6.4 \times 10^6 \text{ m})^2 \quad (54)$$

$$\boxed{\mathcal{R}_{\text{H}_2} = 5.1 \times 10^{25} \text{ molecules s}^{-1}} \quad (55)$$

Therefore, if we were to evolve forwards for 1 Gyr, the total number of molecules that would be lost are

$$\boxed{N_{\text{H}_2, \text{lost}} = 1.6 \times 10^{42}} \quad (56)$$

and so this is comparable to the current hydrogen content of the Earth's atmosphere, approximately a factor of 6 lower.

### 3d. Earth Oxygen Loss

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This calculation will be exactly the same except we now change the mass from  $m \approx 2 \text{ amu}$  to  $m \approx 32 \text{ amu}$ . This drastically changes things due to the exponential terms and so the rate of oxygen loss is an extremely low

$$\boxed{\mathcal{R}_{\text{O}_2} = 1.6 \times 10^{-71} \text{ molecules s}^{-1}} \quad (57)$$

Meaning that over a billion years we wouldn't expect the loss of *any* oxygen. I therefore conclude that over time the abundance of atmospheric oxygen relative to hydrogen will increase (assuming no other sources or sinks).