ISM/IGM Final

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1 Molecules in Clouds and Photodissociation Regions

1.1 A

Carbon is present as C^+ in neutral Hydrogen (HI) regions because it has a lower ionization threshold (11.26 eV) than HI (13.6 eV). The dominant form of ionization is UV photoionization, so this is the case as long as $A_V < 3$. This HI region should be optically thick to UV radiation between 13.6 and 54.4 eV, meaning both H and He will be neutral. Carbon should be the most abundant ionized atomic species. In this case, it is reasonable to assume that the main contributor towards the electron population is from the ionization of carbon, thus $n_e \sim n_{C^+}$ is a reasonable approximation.

1.2 B

The lowest two vibrational/rotational energy levels for H_2 have wavelengths of 28.18 μm and 17.03 μm. These transitions correspond to a temperatures of 510.8 K and 845.3 K respectively. Assuming these states could be readily excited, these transitions allow the cooling of a molecular cloud down to 510.8 K. Below this temperature, CO becomes essential. Its J(1-0) transition has λ = 2.6 mm, and thus a corresponding temperature of 5.54 K. Although H_2 is essential for cooling in general, CO cooling becomes vital in the formation of molecular clouds, which have temperatures around 10 - 20 K.

1.3 C

As given in Draine pg. 368, the linewidth σ_v in a virialized cloud is given as $<\sigma_v^2> = 6GM/5L$, where L is the characteristic size of the cloud (L = 2R). Assuming that $R \propto \sigma_v^2$, then the gas surface density, Σ is given as

$$\Sigma = \frac{M}{A} \propto \frac{M}{R^2} \propto \frac{\frac{5\sigma_v^2 L}{6G}}{0.5L\sigma_v^2} \propto \frac{\sigma_v^2 L}{\sigma_v^2 L} = \text{constant}. \tag{1}$$

Thus, the gas surface density is constant assuming a virialized molecular cloud.

For $L_{CO} = \left(\sqrt{2\pi}T_B\sigma_v\right)\pi R^2$ and $M_{gas} = \Sigma\pi R^2$, the relationship between CO luminosity and gas mass can be readily seen to be

$$\frac{M_{\text{gas}}}{L_{\text{CO}}} = \frac{\Sigma}{\sqrt{2\pi}T_B\sigma_v} \tag{2}$$

This relationship is then a function of easily measureable quantities, the brightness temperature of the CO line (T_B) and the linewidth σ_v, with the surface gas density being a constant. There is then a linear relationship between gas mass and CO luminosity.

1.4 D

The CR ionization rate as traced by $N(H_3^+)/N(H_2)$ is given as

$$\xi \approx (k_{16.9} + k_{16.10})n_H x_e \frac{N(H_3^+)}{2N(H_2)}(1+\phi_s)^{-1} \tag{3}$$

where ϕ_s is given as

$$\phi_s = \left(1 - \frac{x_e}{1.2}\right)\left(\frac{0.67}{1+(x_e/0.05)}\right) \tag{4}$$

x_e can be estimated from the ionized fraction of Carbon as x_e=x(C^+). For the provided numbers, the range of possible ionization rates is $1.28\times10^{-18}s^{-1} < \xi < 1.28\times10^{-16}s^{-1}$. The values used in Draine vary, but are in the neighborhood of 1.0 to 6.0 $\times10^{-16}s^{-1}$. These sit at or above the given upper limit.

1.5 E

The isothermal sound speed for cool (T∼10 K) gas expected of molecular clouds is on the order of 1 km/s. For shocks colliding at roughly twice the velocity dispersion of the MW's disk, the shock types are expected to be either C or C*, but not J, in a MHD two-fluid shock (as relevant for molecular clouds). This implies that there is no viscous jump between the upstream and downstream gas. In the C* case, the neutrals smoothly transition from supersonic to subsonic pre-shock, then back to supersonic as the gas cools in the post shock region. These cases are valid assuming a subalfvenic ion velocity. Two-fluid MHD shocks are not expected to dissociate H_2 for shock speeds below 40 km/s. In this case then, H_2 cooling is significant, as its vibrational/rotational states will be excited in the shock heating of the molecular cloud.

In the shocked regions, the resulting heating may allow for reaction 33.24 to take place, converting C^+ and H_2 to CH^+ and H with the input of 0.40 eV. This requires gas heating above 10^3 K. Draine & Katz (1986) model the chemical evolution MHD shocks as applied to molecular clouds, and found that C-type shocks in these clouds could generate CH^+. They compare their results to three molecular clouds (ξ Per, o Per, and χ Oph) and are able to construct models that produce the observed CH^+ (with other observational constraints) reasonably well. These models required shock velocities between 7 and 12 km/s.

1.6 F

Assuming a uniform density molecular cloud, an ionization and shock front that propogates through the cloud resulting from the formation of a star will switch between a few different forms during its journey outward. The initial ionization front will be a strong, R-type front which propogates outward at speeds much greater than twice the isothermal sound speed (much greater than roughly 20 km/s). Once the front reaches speeds close to twice the sound speed, usually when R∼R_{SO}, the front generates a shock wave ahead of itself. The ionization front continues to move through this shocked (heated and accelerated gas), but does so now as a weak D-type shock. The ionization front is now trapped behind the hydrodynamical shock front, as it becomes subsonic. They both continue to travel outward, but decelerate over time.

The D-type shock propogating outwards causes ionized gas to flow outward at roughly the sound speed. There is a large pressure jump between the ionized and neutral gas (P is larger in the nuetral gas). This pressure jump is responsible for accelerating ionized gas away from the ionization front (i.e. it pushes the ionized gas outward).

2 Supernovae and Winds in the ISM

2.1 A

The mass flux of the expanding wind is readily given as $\dot{M} = 4\pi r^2 \rho v_w$. In order for the velocity of the wind to be constant as the wind expands, the density profile must go as r^{-2}.

2.2 B

The typical velocity dispersion of an elliptical galaxy is on the order of 200 km s^{-1}. Assuming an AGB wind velocity appreciable to this velocity (just taking v_w = 200 km s^{-1}), Eq. 36.28 in Draine gives the temperature of a postshock region for strong shocks. This equation requires knowledge of the mean molecular weight of the gas, which can range from 0.609 m_H to 1.273 m_H for ionized and neutral gas respectively. Taking μ as a free parameter, the temperature of the post shock gas ranges from 5.5×10^5 K to 1.16×10^6 K for fully ionized and neutral gas respectively. This temperature range corresponds to wavelengths of 26 nm to 12.4 nm, both of which are in the FUV/UV range. Cooling radiation from this gas should be at wavelengths at and below FUV.

2.3 C

Using a massive O star for the computation, an O star has wind velocities between 1500 and 2500 km/s, and mass loss rates between $10^{-6.5}$ and 10^{-5} $M_\odot$ yr^{-1}. For the sake of this computation, I will take V_w = 2000 km/s and $M_\odot = 5\times10^{-6}$ $M_\odot$ yr^{-1}. The rate of mechanical energy deposit in the wind is given as $\dot{E} = \dot{M}V_w^2/2$. Assuming this wind deposits mechanical energy at this rate for the entirety of the O star lifetime, this should give an upper limit for the deposited mechanical energy. It is certainly the case that the onset of radiative cooling will remove some of the deposited energy. The lifetime of an O star is around 10 Myr, but they quickly progress through the main sequence during that time. I will take 5 Myr as the lifetime of this hot wind, which gives a total deposited mechanical energy of 0.995 E_{51} erg, which I will just round to 1.0 E_{51} erg. From Draine, the typical energy deposited by a Type II supernova will have $E_{51} \approx 1$ to 20 erg. Given my rough estimate, the energy deposited by the wind is comprable to but certainly less than the energy deposited by the supernova.

2.4 D

Frankly, I am not terribly sure of how to properly estimate this. The accelerated ISM will be swept up during the Sedov-Taylor phase of the evolution, and also during the subequent snowplow phase (mainly in the latter as the ST phase ends after the swept up mass is comprable to the mass of the stellar ejecta).

Anyway, taking the simple approach and setting $E_{ej} = M_{ej}V_{esc}^2/2$, where M_{ej} is the total swept up mass that can escape the galaxy, and E_{ej} is the energy of that mass. Assuming that 100% of the supernova energy goes into pushing the ISM outward (in reality, the effeciency is less than 100% due in part to radiative losses), the total amount of mass than can be ejected by a supernova with $E_{51} = 1$ and $V_{esc} = 500$ km/s is 402 $M_\odot$.

2.5 E

Using Table 42.1 from Draine, and the text in section 42.3, the supernova rate for the Milky Way can be readily derived assuming the Chabrier IMF. This is given in the text directly as 0.014 yr^{-1}. The rate per solar mass of star formation is given as

$$\frac{\text{Type II SN rate}}{M_\odot} = < M >^{-1} \frac{\text{mass}}{\text{total mass}} = 0.011 \tag{5}$$

where the mass/total mass is taken for stars with $M > 8$ $M_\odot$. Assuming 5% of these supernova have their gas ejected from the disk, then the amount of gas ejected per solar mass of star formation is given as $0.05\times0.011\times M_{esc}$, were M_{esc} is the answer from part D. Thus, using the possibly incorrect answer from Part D, 0.22 $M_\odot$ of gas is ejected for every 1 $M_\odot$ of star formation.

2.6 F

The McKee & Ostriker model gives that the ISM pressure relates to the supernova rate per unit volume as:

$$\frac{P}{k} = S_{-13}^{0.77} n_o^{-0.15} \times 5700 \text{ cm}^{-3} \text{ K}. \tag{6}$$

Taking $S_{-13} = 12.0$ (ten times the observed rate in the MW), and n_o to be unity (the mean number density of the ISM), the resulting pressure for a star forming galaxy would be $P/k = 3.86\times10^4$ cm^{-3} K. The Bonnor-Ebert mass is given as

$$M_{BE} = 0.26 \left(\frac{T}{10\ K}\right)^2 \left(\frac{10^6 \text{ cm}^{-3} \text{ K}}{P/k}\right)^{1/2} M_\odot \tag{7}$$

Using the calculated pressure, and assuming a molecular cloud with T$\sim$ 10 - 20 K, M_{BE} = 1.32 - 5.28 $M_\odot$. This is quite large and would seem to imply that heavy star formation (and thus a large supernova rate) in young galaxies suppresses supsequent star formation of low mass stars, and favors that of higher mass.

3 Two Phase Interstellar Medium

See attached

References

[1] Draine, B.T., Katz, N. *Magnetohydrodynamic shocks in diffuse clouds. II - Production of CH(+), OH, CH, and other species* ApJ, Vol. 310, p. 392-407, Nov. 1986