THE C/CO RATIO PROBLEM: CHEMICAL EFFECTS OF TURBULENCE

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Abstract. We discuss the suggestion that the chemistry in a photon-dominated region is coupled to that in the UV-shielded region behind it by turbulent transport processes. In addition to diffusion time-scales, we discuss why MHD waves will likely cause, instead of prohibit, transport.

1. On the C/CO Ratio Problem

The study of interstellar chemistry has so far focused mainly on two physical regimes; regions subject to abundant ultraviolet photons and regions that are shielded from UV photons. The former are often referred to as photon-dominated regions (so-called PDRs) where the chemistry is dominated by photon-related reactions, and the latter are often thought to be cosmic ray-dominated regions (hereafter CDRs) where cosmic rays sustain the ion-neutral reaction scheme.

The large observed C/CO ratio (~ 0.1) in molecular clouds has been a major challenge to theoreticians working on either regime (cf. Sorrel 1992). One common opinion in the field is that the clumpiness of a cloud allows an enhanced UV penetration into the cloud interior that will dissociate the molecules and create many small photon-dominated regions on the clump surfaces. One severe difficulty with this picture, however, seems to be the large observed abundances of many large organic molecules. Since large organic molecules do not survive UV photodissociation in PDRs, the observed large organic molecules must be deep inside the clumps, which requires the co-existence of abundant neutral carbon (Chièze et al. 1991). The co-existence of neutral carbon with CO in the same volume is strongly indicated by the similarity of their line profiles (cf. Walker et al. 1993) and the tight correlation between their emission intensities (cf. Tauber et al. 1995).

2. On Turbulent Transport and Its Time-scales

What feasible mechanism can bring a lot of neutral carbon deep inside each clump without those UV photons that also destroy large organic molecules? An easy choice seems to be particle transport, which is known to occur universally in random gas motions. Xie, Allen & Langer (1995, hereafter XAL) formulated the idea in the framework of the Prandtl mixing-length theory for turbulent diffusion and found that the transport may give rise to a C/CO ratio in accord with observations.

Transport of particles occurs as a result of molecular diffusion. If there is a wind, convection, or a large-scale random component in gas motions, then the transport due to any of these processes is likely to dominate over molecular diffusion because of the much larger spatial scales and amplitudes over which these processes occur in interstellar clouds. In general, random motions cause fluctuations of a physical quantity in a non-uniform multi-component gas. Defining the fractional abundances $f_i = n_i/n(\mathrm{H_2})$ for species i, the transport flux can be written as (cf. Colegrove et al. 1966; XAL), $\phi_i[\mathrm{cm^{-2}\ s^{-1}}] = n(\mathrm{H_2}) < V_t \delta f_i >= -Kn(\mathrm{H_2})\frac{df_i}{dz} = -Kn_i(\frac{1}{n_i}\frac{dn_i}{dz} - \frac{1}{n(\mathrm{H_2})}\frac{dn(\mathrm{H_2})}{dz})$, where $<>$ denotes the time average of a quantity, and the diffusion coefficient $K[\mathrm{cm^{-2}\ s^{-1}}] = < V_t L >$ with V_t being the velocity for the random motion and L the mixing-length scale.

Now with a transport term, the continuity equation at a cloud position is $\frac{\partial n_i}{\partial t} + \frac{\partial \phi_i}{\partial z} = P_i - L_i$ where P_i and L_i are the chemical production and loss terms, respectively. Defining a chemical time-scale, $\tau_i^{chem} = n_i/(P_i - L_i)$, and a diffusion time-scale, $\tau_i^{diff} = n_i/\frac{\partial \phi_i}{\partial z}$, the continuity equation reduces to a simpler form,

$$\frac{\partial n_i}{\partial t} = n_i(\frac{1}{\tau_i^{chem}} - \frac{1}{\tau_i^{diff}}). \qquad (1)$$

Defining a time constant, $\tau = R^2/K$, that is typically large compared to the chemical time-scales, Williams & Hartquist (1991) argued that diffusion will not be important. It is not difficult to see that the real situation is much more complicated than this. First, $\tau = R^2/K$ has essentially no physical meaning in the formulation. Both the chemical and diffusion time-scales in the above continuity equation are position-, time-, and species-dependent. Even when we fix the question to a particular moment, both time-scales still depend in a complicated manner on the detailed physical and chemical conditions at a cloud position. The diffusion time-scale may be simplified to $\tau_i^{diff} = H_i H/K$, where the scale heights $H_i = n_i/\frac{\partial n_i}{\partial z}$ and $H = f_i/\frac{\partial f_i}{\partial z}$, but it would not reduce to $\tau = R^2/K$ without orders of magnitude error. Secondly, diffusion is generally coupled to the highly non-linear chemistry and cannot be treated as a pure diffusion in this case; a small change in some key species due to diffusion between neighboring layers can boost the local generation or destruction of certain species (XAL).

3. In the Case of MHD Waves

It is quite possible that the observed "turbulence" in molecular clouds is due to magneto-hydrodynamic waves (MHD waves). A perfectly coherent wave particle carried up will be carried down in a cycle, so there will be no net transport. Would MHD waves be perfectly coherent in molecular clouds, given their irregularities in magnetic fields, densities, and other physical conditions and even their star forming activities? The magnetic Reynolds number is so large that any such waves will be turbulent and random in nature on relevant spatial scales (Myers & Khersonsky 1995), which will naturally lead to net particle transport (Lindzen 1971; Hunten 1975). In fact, even if waves are perfectly coherent, the non-uniform and non-homogeneous chemistry will still unavoidably cause a net transport of certain chemical species, as chemicals carried up could be destroyed and will thus never be carried down, or vice versa. Lindzen (1971) suggested that the diffusion coefficient in the case of interrupted waves can be expressed as $K \sim v\lambda/(\pi x)$, where v is the average wave velocity, λ is the averaged wavelength, and x is the number of wave cycles (non-integer) before being interrupted. Notice that diffusive transport along the average magnetic field would be enough to have significant effects on the chemistry. The simple-minded approach outlined by XAL is not sensitive to the nature of the observed "turbulence" in molecular clouds.

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