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Cosmic Evolution of Extragalactic C I, C II, and CO Luminosity

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Carbon is the fourth most abundant element in the Galaxy with an abundance of $\sim 4 \times 10^{-4}$ relative to hydrogen. Of all abundant metals it is the easiest to observe in the interstellar medium (ISM). Carbon can be found in four dominant forms: dust grains, C II, C I, and CO. The latter is the most abundant molecule (next to H_2) in molecular clouds. All three gas-phase forms produce strong sub-mm wavelength emission lines and are the principal tracers of the warm and dense neutral phases of the ISM.

We calculate the gas-phase abundances of neutral carbon (C I), ionized carbon (C II), and carbon monoxide (CO) as a function of cosmic time or redshift z in an idealized scenario of galactic evolution. The total gas-phase abundance of any metal is the product of the fractional abundance of the metal and the total amount of gas remaining in a galaxy. All galaxies are born with metallicity $Z = 0$ and a gas mass fraction, $\mu = M_{\rm gas}/M_{total} \approx 1$ where $M_{total} = M_{gas} + M_{stars}$. As star formation proceeds, a fraction of the mass consumed is locked-up permanently inside long-lived, low-mass stars and stellar remnants (white dwarfs, neutron stars, and black holes). The remaining consumed mass is eventually returned to the ISM via planetary nebulae, red giants, AGB stars, and supernovae, polluted with elements such as carbon, oxygen, and iron. The grain abundance regulates the size and photoelectric heating rate of photodissociation regions (PDRs) in Giant Molecular Clouds, and thus helps determine the strength of the [C II] 158 μm line. The mm and sub-mm wavelength lines of these species may provide a new tool for studies of cosmology, galaxy evolution, and chemical enrichment of the ISM.

Closed Box Model: We use the formalism outlined by Tinsley (1980) to calculate the total gas-phase abundance of carbon as a function of gas mass fraction μ. In a closed-box model of galactic evolution and under the assumption of instantaneous recycling of metal enriched gas for stars above a critical stellar mass, the metallicity of the gas is given by $Z = y \ln (1/\mu)$ where y is the *yield*, the mass of new metals ejected by stars when 1 unit of mass is locked-up into stars. The total ISM abundance of a species such as carbon is given by $M_C = y_C M_{gas} \ln (M_{total}/M_{gas})$ where y_C is the yield of carbon.

Infall rate = star formation rate: If infall of pristine ($Z = 0$) matter plus the mass returned to the ISM by mass loss just balances the star formation rate, the mass of the ISM remains constant. Tinsley (1980) shows than in this case, $Z = y[1 - \exp(1 - 1/\mu)]$ and the abundance of C in the ISM is given by $M_C = y_C M_{gas} [1 - \exp(1 - M_{total}/M_{\rm gas})]$

For simplicity, we assume that the properties of molecular clouds remain constant with increasing redshift, except that the minimum temperature of the clouds, $T_{\rm cl}$, remains somewhat above that of the co-moving temperature of the cosmic microwave background, T_{CMB}. That is $T_{\rm cl} = T_{CMB}(1+z) + T_{\rm off}$. We assume that the fraction of ISM mass in the form of molecular clouds and the fraction of carbon locked up in grains remain constant with changing μ. Then the fraction of gas-phase carbon in the C I, C II, and CO phases is determined by the physics of photodissociation regions. As shown by Langer (1976) and Tielens & Hollenbach (1985), the thickness of the C I-bearing layer in a molecular cloud is, to first order, determined by the attenuation of UV radiation by dust grains. Self-shielding of the CO lines may play a secondary role in determining the location of the C I-to-CO transition.

If the grain properties and fraction of metals in grains are independent of metallicity, then the mass ratios, M(C I)/M(CO) and M(C II)/M(CO), should increase with decreasing Z. This general trend can be tested by observing these species in low-metallicity dwarf galaxies such as the LMC and SMC. Observations of the $z = 2.286$ protogalaxy IRAS F10214+4724 show that the C I lines are about 3 times stronger than the CO lines (Brown & Vanden Bout 1992). The luminosity of spectral lines is determined by excitation conditions within the emitting region. Most CO emission in the Galaxy is produced by gas with volume densities above 10^2 cm^{-3}, and the mm-wave lines of CO are optically thick and thermalized. C I and C II can be excited in: (1) the low-density warm and hot phases of the neutral ISM, where the excitation is sub-thermal and the lines are optically thin; and (2) in the high-density outer layers of molecular clouds where the lines are nearly thermalized and optical depths approach unity. Reasonable estimates for the parameters of the ISM demonstrate that Galactic C II emission is dominated by warm edges of molecular clouds where the lines are thermalized. A similar argument applies for [C I], which is easier to excite at lower temperatures since the 609 μm line lies only 23.6 K above the ground state. Thus, [C I] is easier to excite than [C II] in PDRs.

The conclusions from our study are:

- The gas-phase carbon abundance as a function of gas mass fraction is relatively insensitive to the galactic evolution model parameters (Fig. 1); the epoch of maximum gas-phase carbon abundance depends mostly on the star formation history of a galaxy.

- In a closed-box model of galactic evolution, the maximum abundance of carbon in the ISM occur when the gas mass fraction of a galaxy $\mu \approx 0.3 - 0.4$.

- The total abundance of carbon in the ISM of galaxies was substantially greater in the past. The star formation histories for galaxies of various Hubble types given by Sandage (1986) imply that the sub-mm line luminosity of early-type galaxies peaks at early epochs, while later Hubble types reach maximum luminosity at progressively later times.

- The total luminosity ratio of [C I]/CO and [C II]/CO increases with decreasing metallicity. The sub-mm fine-structure cooling lines are expected to be relatively brighter than CO in the early Universe and in less chemically evolved galaxies at the present.

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Figure 1. The relative gas-phase concentration of carbon (M_{carbon}/M_{total}) vs. gas mass fraction, $\mu = M_{gas}/M_{total}$ for a closed-box model. The vertical arrows show the present-day value of μ. The yield of carbon, y_C, is normalized to produce a gas phase carbon abundance of 3×10^{-4} ($\mu = 0.05$) at the present.

Figure 2. Carbon content of galaxies of various Hubble types as a function of cosmic time or redshift ($\Omega_o = 1$ universe) for closed-box model and star formation models of Sandage (1986). The present-day gas fraction, μ, is assumed to be only a few percent in early type galaxies, about 10% for Sc spirals, and about 20% for irregulars. The carbon abundances are normalized to the same galactic mass. The maximum gas-phase carbon abundance (and C-line luminosity) occurs when $\mu \approx 0.3 - 0.4$. For early-type galaxies, this corresponds to $z \geq 5$, and at progressively lower redshifts for later Hubble types.

Fig. 1

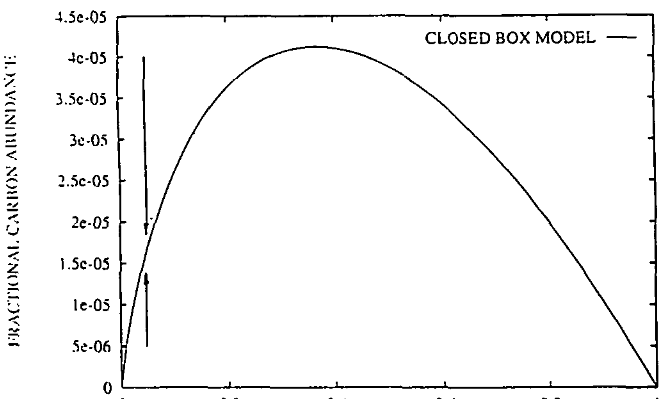

Fig. 2