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Isotopic ratios and fractionation in the local Universe

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Abstract. The knowledge of isotopic abundances is important in galaxy evolution studies because isotopes provide diagnostics for the chemical enrichment in galaxies over time. While measurements of isotopes in large sample of stars would be ideal to determine the fossil record of the enrichment history, in practice this is hampered by the need of very high resolution, high signal-to-noise spectroscopic data. A complementary, or alternative, method is to measure isotopic ratios from observations of gas-phase interstellar medium (ISM) isotopic abundances. In this proceedings I shall review the observations of the most abundant fractionated species in nearby galaxies and recent modeling efforts aimed at investigating the physical and chemical conditions that can lead to a large spread of isotopic ratios in external local galaxies.

1 Introduction

It is now well established that the cooler ($<$ few thousands K) and denser (> 100 cm^{-3}) parts of our own as well as other galaxies are pervaded by molecules. Such dense and cool regions are of course important in themselves as they are the sites of star formation. But they are also important for our understanding of how galaxy evolve and in tracing the results of the nucleosynthesis in different types of galaxies where the star formation processes themselves may differ. Of particular use are the isotopologues of the main elements: carbon, nitrogen and oxygen.

In our own galaxy isotopes variations at different scales give clues about the link between the ISM and solar-like systems. On the other hand, isotopic measurements at larger scales are crucial for the understanding of the CNO cycles (nucleosynthesis), especially of how the yield differs between low mass and high mass stars and hence how the ISM enrichment is affected by such differences. Ideally one could measure isotopes in large sample of stars and determine the fossil record of the ISM enrichment history; in reality this is not possible due to limitations in resolution, and sensitivity. Instead we can measure isotopic ratios from observations of gas-phase ISM isotopic abundances [1]

In this procedings, we shall concentrate on carbon and nitrogen isotopic ratios in external galaxies. But before we move on to review our knowledge of isotopic ratios in other galaxies, it is worth noting that in the local ISM, variations in the ^{14}N/^{15}N ratio (from their solar value of ~ 440, [2]) and in the ^{12}C/^{13}C ratio (from their solar ratio of ~ 69, [3]) point to multiple origins as stellar nucleosynthesis alone can not lead to the observed range in the

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Milky Way. A possible origin for the large ranges observed is chemical fractionation in the ISM. For example, the large spread in the measured $^{14}N/^{15}N$ ratio, ranging from ∼100 for meteorites, comets and protoplanetary disks to ∼1000 in pre-stellar and star-forming cores could be a combination of evolutionary effects (e.g. from protostellar cores to late stages of star formation) as well as different gas densities and temperatures ([4]; [5]; [6]; [7]).

Several theoretical "local" studies strongly confirm significant variations of the isotopic ratio as a function of time and gas density (e.g. [8], [9]). For example, [8] presented a chemical model where comprehensive ^{13}C and ^{14}N networks were included and found variations in the isotopic ratios both across time as well as molecules, and in particular they found that both nitriles and isonitriles are very depleted in ^{13}C, a result with potential consequences for isotopic ratios derived using HCN, HNC and CN.

It may therefore not be surprising that extragalactic studies do not find agreement on a single value for either of these two ratios.

2 Nitrogen and Carbon Fractionation in external galaxies

Isotopic abundances are important in galaxy evolution studies because isotopes provide diagnostics for the chemical enrichment in galaxies over time.

In particular, let us consider the $^{14}N/^{15}N$ ratio: the latter is often used as an indicator of stellar nucleosynthesis because the two isotopes are synthesized in stars in different ways during the CNO cycle of massive stars (e.g. [10]), with ^{14}N being the primary product at low metallicity (e.g.[11]), while ^{15}N may be overproduced during the novae phase. Carbon, also, exists in the form of two stable isotopes, ^{12}C and ^{13}C. The former is synthesised via Helium burning in both low-mass and massive stars in a short timescale while the latter is mainly expected to be synthesised through the CNO cycle in asymptotic giant branch (AGB) stars through slower processes and hence its 'distribution' to the ISM is less direct than in the case of ^{12}C.

While of course differences in nuclesynthesis yields will lead to differences in isotopic ratios, other processes, unrelated to stellar nucleosynthesis, may be important too in affecting the isotopic composition of the ISM. For example, the cold gas in galaxies may favour low-temperature exothermic ion-neutral exchange reactions (e.g. [12], [13]) which will increase ^{13}C in species such as CO and HCO^+, although in some cases energy barriers do exist and in order to quantitatively determine the role of such reactions in augmenting the ISM of fractionate species, the presence of such barriers need to be systematically checked [8].

However, we note that the average gas in galaxies will not be at 10 K: much of the gas will be in photo-dissociation regions (PDRs). In PDRs, where the gas is exposed to UV radiation, isotope-selective photo-dissociation and other mechanisms may be important. Moreover, in some specific environments, e.g. in starburst regions or in the vicinity of AGN, the gas is dense ($\geq 10^4$ cm^{-3}) and warm (> 50 K).

In summary, the relative importance of these processes, and the existence of additional processes not yet considered, is still unclear. A first step towards determining the importance of these mechanisms requires an attempt at quantifying whether, for a fixed nucleosynthesis yield, chemical fractionation actually leads to any of the variations in isotopic ratios we observe in galaxies: Table 1 contains a (non exhaustive) summary of the observational values of $^{12}C/^{13}C$ and $^{14}N/^{15}N$ across different types of galaxies, combined from Tables 2 from [14] and Table 1 from [15].

Table 1. $^{12}C/^{13}C$ and $^{14}N/^{15}N$ measured in external galaxies.

Galaxy	type	$^{12}C/^{13}C$	Mol.	Ref.
NGC 253	starburst	~ 40; 30 – 67	CN	[18]; [19]
NGC 253	starburst	~ 27 – 70	CS	[20]; [21]; [18]
M82	starburst	> 40	CN	[22]
NGC 253	starburst nucleus	~ 21	$C^{18}O^a$	[23]
NGC 4945	starburst nucleus	6–44	CN	[19]
VV 114	LIRG	~ 230	CO	[24]
NGC 1614	LIRG	~ 130	CO	[25]
Mrk 231	ULIRG	~ 100	CO, CN	[18]
Arp 220	ULIRG	~ 100	CO	[26]
Arp 193	ULIRG	~ 150	CO	[27]
Cloverleaf	ULIRG z = 2.5	100 – 200	CO	[28]
Eyelash	ULIRG z = 2.3	~ 100	CO	[29]
LMC	0.5 metal	~ 49	H_2CO	[30]
NGC 1068	AGN+starburst	~ 50 ;24–62	CN	[31]; [19]
NGC 4258	AGN	~ 46	HCO^+	[32]
NGC 3690	AGN+starburst	~ 40	HCO^+	[32]
NGC 6240	AGN+starburst	~ 41	HCN	[32]
NGC 6240	AGN+starburst	300 – 500	CO	[27]; [33]
IC 342	spiral local	> 30	CN	[22]
MA0.89	spiral z = 0.89	~ 27	HCN, HCO^+, HNC	[34]
MA0.68	spiral z = 0.68	~ 40	HCN, HCO^+, HNC	[35]
Galaxy	type	$^{14}N/^{15}N$	Mol.	Ref.
NGC4945	starburst	200-500	HCN	[36]
LMC	0.5 metal	111(± 17)	HCN	[37]
Arp220	ULIRG	440 (+140,-82)	HCN, HNC	[38]
NGC1068	AGN+starburst	> 419	HCN	[39]
IC694	starburst	200-400(?)	HCN	[32]
LMC	0.5 metal	91(± 21)	HCN	[30]
M82	starburst	> 100	HCN	[22]
Galactic Center	standard with high ζ	≥164	HNC	[40]

3 The sensitivity of carbon and nitrogen fractionation to the physical conditions of a galaxy

As mentioned already, several theoretical studies have concentrated on the variations of carbon and nitrogen fractionation in low temperature (up to 50K) ISM ([8]; [16]; Colzi et al. 2022 this proceedings). All these studies in general do find that isotopic ratios display significant variations with density and cosmic ray ionization rates. In [15] and [14] we explored a higher temperature parameter space and performed a theoretical study of the ISM nitrogen and carbon fractionation to determine physical conditions that may lead to a spread in these ratios from the solar values. For those studies we used the publicly available ode UCLCHEM ([17]; https://uclchem.github.io/) which is a time dependent gas-grain chemical model. The already quite comprehensive chemical networks were augmented with the known exchange reactions from [8] and [9]. Large grids of models were ran spanning densities from 10^4 to 10^6 cm^{-3}, temperatures from 50 to 200 K, cosmic ray ionization rates from the galactic values of $\sim 10^{-17}$ s^{-1} to a factor of 10^4 higher, and radiation fields from 1 to 100 Draine (or 2.74×10^{-3} erg/s/cm^2).

Two key results from these two studies are that (i) in general fractionation (of C and N) does not seem to be very sensitive to temperature in the explored range; and (ii) the CO

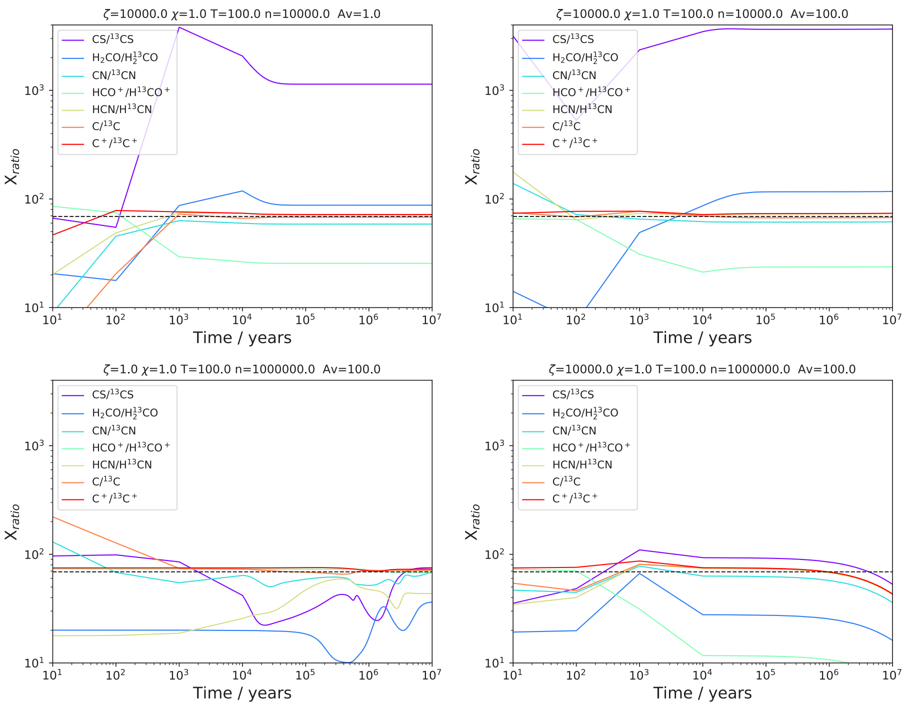

Figure 1. Figure 5 from [14] showing the effects of varying the cosmic ray ionization rate on the ISM chemistry of carbon isotopes.

fractionation is fairly constant implying that a high $^{12}C/^{13}C$ in CO (e.g. >100, see Table 1) must be a product of nucleosynthesis rather than ISM chemistry. Furthermore it was found that a high cosmic ray ionization rate and/or a high radiation field leads to a much more variable fractionation for most species (see Figure 1). This is particularly relevant for AGN-dominated galaxies or starburst galaxies. Finally there are clearly differences in fractionation among molecules: for example, the fractionation of CS is always lower than in other species (see Figure 2). More specific results, for carbon and/or nitrogen fractionation have been determined by these studies and can be found in the aforementioned papers. We can certainly conclude that, as previously found by other authors ([8]) there are always large variations in the isotopic ratios in the species investigate.

So does ISM fractionation in the ISM of galaxies contribute to the observed variations? It is clear that - with time, physical parameters, and across species - isotopic ratios vary in the ISM. The question then now is whether such changes are reflected in the observational ranges observed as reported for example in Table 1.

We already mentioned that the large $^{12}CO/\,^{13}CO$ observed for e.g. in starburst galaxies is a product of nucleosynthesis and not ISM fractionation. However, it is interesting to note that qualitatively it was found that different models can reproduce most of the observations. So for example, for starburst galaxies all the best fit models have a higher than galactic radiation field as well as cosmic ray ionization rate, while for AGN-dominated or composite galax-

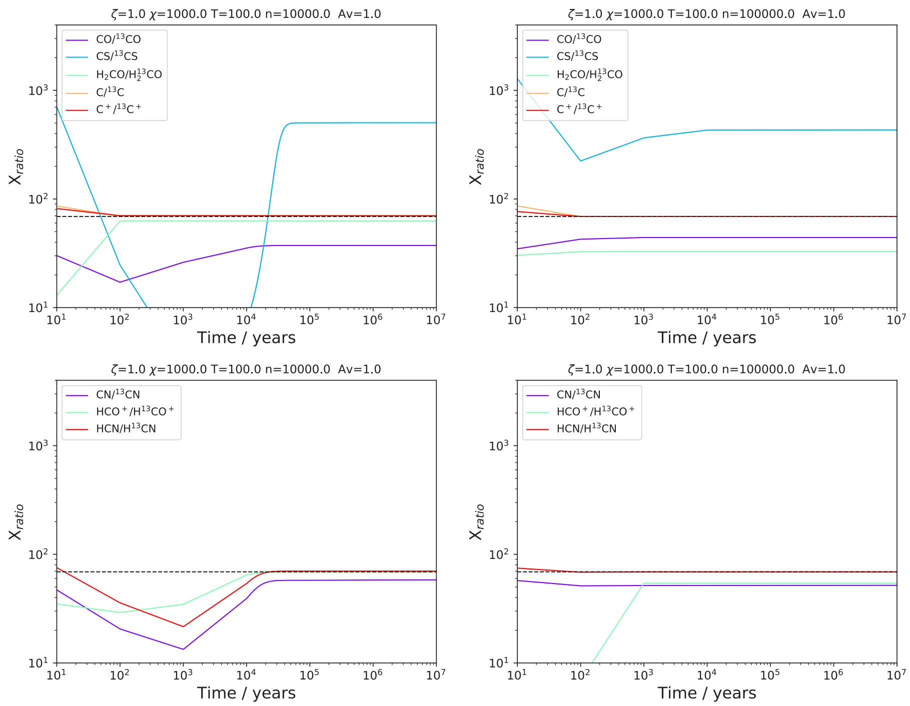

Figure 2. Figures 9 and 10 from [14]. Top: $^{12}C/^{13}C$ for selected species in extended gas in starburst galaxies. Bottom: as Top Figures but for dense gas in starburst galaxies.

ies the best fit models imply a large reservoir of PDR gas plus a considerably high density component.

It is worth to conclude with a note of caution when interpreting isotopic ratios in external galaxies: most current measurements are unable to determine such ratios for linear scales less than 50 pc or so. Only very high angular resolution observations will truly allow us to disentangle the effects of different nucleosynthesis yields from local chemical effects.

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