# The Interstellar and Circumgalactic Media at low and high redshift as traced by Atomic Carbon and Carbon Monoxide

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**Abstract.**
A different chemistry of the interstellar medium (ISM) is expected in the circumgalactic medium (CGM) gas where high-energetic particles (i.e. cosmic rays) seem to be produced in-situ by the hot X-ray gas, as it is observed in the Perseus cluster. This very different astrochemistry, where extreme gas-dust thermal decoupling is expected, and where CO can be destroyed over large mass-scales, is the subject of the investigation briefly reported here. We introduce an on-going project aiming at studying the properties of the CGM of two clusters at low and high redshift using their molecular gas tracers and thermal emission from dust.

## 1 Circumgalactic Medium in Galaxy clusters: Why?

The circumgalactic medium (CGM) is the site where galaxies exchange their gas with the surrounding environment via inflows from the CGM to the galaxy and/or outflows powered by AGN and star formation which may deposit chemically enriched material in the CGM. The CGM therefore represents a site where physical conditions might be different from the less extreme interstellar medium of galaxy discs. It is expected that in galaxy clusters (GCs) with intense SF and/or AGN activities the CGM (and intracluster medium, ICM) contain large amounts of lower-density, galaxy-expelled, molecular gas and dust, which would then be subjected to a high-energy particle-dominated chemistry [see, 4–7, 13, 21, 22].

Strong $H_2$ winds are expected from galaxy cluster members with SFR $\sim$ 150-250 $M_{\odot} yr^{-1}$, injecting gas and dust into the CGM/ICM [7]. In these media, dust is very efficiently cooled by thermal emission while no longer heated by the far-UV photons (from the distant SF inside the BCG) nor by ambient CRs.

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## 2 Gas tracers

In this scenario, the traditional way to estimate the amount of molecular gas, M($H_2$), and its physical properties may not be valid and need further investigations.
For decades molecular gas has been estimated inside galaxies from the Carbon Monoxide (CO) emission luminosity (from the $X_{CO}$ factor) and from the dust emission. But, how will the standard $H_2$-tracing methods be impacted in extreme environments? How does star-formation happen away from the central galaxy and how is the initial mass function (IMF) affected?

In fact, high-energetic particles, like cosmic rays, which are copious in sites of intense star formation, have the power to destroy the CO molecules, enhancing neutral and ionised Atomic Carbon (CI, $C^+$). The high-energetic particles may become the fundamental regulators and power sources in these environments. The thermal state of UV-shielded dense gas is altered, dust might be too cold and undetected because less hit by FUV photons which are too far away. This might have an effect on the Jeans mass, the gas fragmentation properties and the characteristic mass of young stars, affecting the condition of star formation and very likely the stellar initial mass function (IMF) [12, 16, 19].

Indeed in the past decade chemical-physical models associated to simulations show how CO loses its molecular hydrogen tracing capability in low metallicity environments and in violent media (due to starbursts/AGN activities) and CI and $C^+$ remain the dominant form of carbon [2, 8, 9, 17]. Therefore a thorough investigation of the interstellar/circumgalactic and intergalactic media must span a wide range of available tracers, to probe density, temperature, ionisation state, etc.

With the advent of improved receivers (at IRAM, APEX) and larger facilities (ALMA), the access to broader frequency ranges and higher sensitivity allows to observe the two CI forbidden lines (492, 809 GHz) and the ionised Carbon, $C^+$ (1.898 THz). These lines have been proven to be a fair tracer of the total molecular gas under a large range of physical conditions. Furthermore, the two CI system is much simpler than the CO, it allows to derive more easily the gas physical parameters (excitation temperature, mass, density,...)[1, 15], tracing the CO-invisible $H_2$ gas where energetic particles destroy CO (leaving behind Atomic Carbon) and because its high-frequency emission is less affected by the CMB[23].

## 3 Observational data

In light of the above, in order to investigate the star formation conditions in extreme environments we have undertaken a study of the gas tracers towards two proto-type galaxy clusters, hosting a powerful AGN in their centre and showing a very turbulent CGM environment. These are excellent candidates to study $H_2$ gas and dust during an episode of elevated SF and AGN feedback.

### 3.1 MACS1931.8-26

MACS1931.8-26 is a cluster at z=0.35 whose core contains a bright central galaxy, a cool core and an AGN. A reservoir of $T_d$=10 K dust is detected in its CGM regions at ~30 kpc from its centre, concomitant with warm gas with high CO(3-2)/(1-0) ($R_{31}$=0.93) ratios with a total cold gas mass (as marked by the CO(1-0) emission) of $\sim 2 \times 10^9$ $M_\odot$ [7].

This result indicates a large ratio between the kinetic and the dust temperature, $T_{kin}/T_d$ and thus a power source other than SF-generated FUV radiation. In this cluster, as in the Phoenix cluster [21], there is either a superdusty CGM/ICM with gas-to-dust ratio of ~10-25 (and discrepancies in the relative distributions of their $H_2$ gas and dust), or we are missing

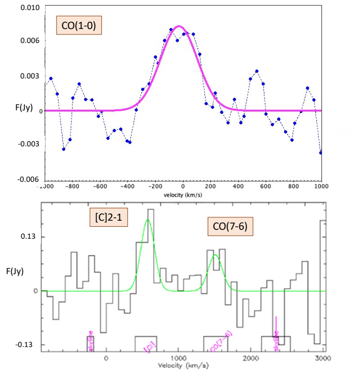


**Figure 1.** Preliminary analysis of the CO(1-0) emission observed at the NRO45m dish and of the APEX/SEPIA660 data of the [CI]2-1 and CO(7-6) lines (Project ID 0106.A-0997(A)) (Andreani et al, in preparation).

$H_2$ gas that would restore the gas-to-dust ratio back to ~100-150. Missing $H_2$ gas could be due to the interferometric observations filtering out the extended diffuse emission and/or to CO-dark gas.

To investigate this issue further, we recently obtained single dish observations with APEX/SEPIA660 of the [CI]2-1 and CO(7-6) spectra and with NRO 45m of the CO(1-0) emission. Preliminary spectra are shown in Figure 1. A quick look at the CO spectrum shows that the single dish CO(1-0) line luminosity is larger than derived from the ALMA 12m data [7], likely indicating that extended emission is missed in the interferometric observations. In addition the APEX data towards [CI]2-1 and CO(7-6) (see, Figure 1) show an unexpectedly bright [CI] compared to the CO(7-6), indicative of cosmic ray heated gas. Additional observations to complement the available data have been requested. The availability of several CO lines and the two Atomic Carbon lines will allow to make a full analysis of the thermal state of the gas, breaking the degeneracy inherent to the CO analysis only.

### 3.2 MRC1138-262

MRC1138-262 is a radio galaxy with a powerful radio-loud AGN hosted by one of the most massive galaxies in formation in the heart of the Spiderweb protocluster. It is one of the best studied high-z objects [11, 14, 20] with a stellar mass of $M_\star \sim 2 \times 10^{12} M_\odot$. It has a complex morphology of merging satellite galaxies surrounded by a giant (~250 kpc) Ly-$\alpha$ halo, tracing a rich proto-intercluster medium in the cluster core. Past ALMA observations of [CI]1-0, and CO(4-3) and APEX observations of $C^+$ show emission across ~50 kpc, while low-surface-brightness CO(1-0) emission in the CGM detected with ATCA reveals the presence of a massive ($\sim 10^{11}$ $M_\odot$) extended $H_2$ gas reservoir [3, 4] which fuels in-situ star formation in the CGM/ICM. All transitions span a velocity distribution far wider than that corresponding to the velocities of the satellite galaxies that lie within the overall molecular distribution.

The detection of extended emission outside the central galaxy was confirmed and enhanced by combining data from the ALMA Compact Array (ACA) with the 12m observations (see Fig 2). Despite the low signal-to-noise ratio the combined data show indeed that the emission is extending far away (~50kpc) from the central galaxy. Further investigation to derive the properties of this extended emission in a quantitative way are underway. The combination of the CO spectral line distribution, the ratio of the Carbon lines and the information on the dust temperature offers a unique set of data to break the degeneracy to derive the gas physical quantities [see for instance 10, 18].

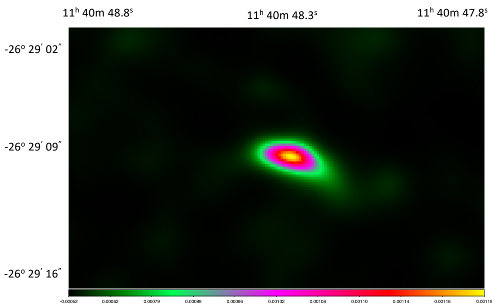


**Figure 2.** Preliminary analysis of the combination of the ALMA ACA and 12m arrays of the CO(4-3) lines (Souvaitzis et al, in preparation).

## 4 Conclusions

We presented a preliminary analysis of the molecular gas towards two clusters of galaxies, which might be considered a good template to investigate physical processes in extreme environments. We argue that the combined use of various gas tracers, together with the combination of observations from diverse instruments accessing different spatial scales, shows its power to infer the physical status of the gas in star forming regions far away from the ISM of galaxy discs. The chemical-physical status of this gas may largely affect the star formation process and the resulting stellar initial mass function.

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