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How do the cosmic rays influence the chemistry in star-forming regions?

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Abstract. Molecular line observations may serve as diagnostics of the degree to which the number density of cosmic ray protons is enhanced in starburst galaxies and galaxies with active nuclei. Results, obtained with the UCL-PDR code, for the fractional abundances of molecules as functions of the cosmic ray induced ionization rate, ζ, are presented. The aim was to identify the dependence of molecular abundances on ζ, in part to enable the development of suitable observational programmes for cosmic ray dominated regions (CRDRs) and stimulate further detailed modelling. Following the results obtained, we have generated indeed successfully a more detailed chemical modelling of the filamentary structure seen in the Perseus Cluster. Predictions of useful tracer molecules to observe for constraining the origin of the heating mechanism in this source were identified and follow-up observations made. The comparison of theoretical predictions with observational results supports the view that cosmic rays, rather than dissipation, provide the likely heating mechanism in the Perseus cluster.

Key words. Astrochemistry – methods: numerical – ISM: abundances – galaxies: ISM – galaxies: star formation – submillimetre: general

1. Introduction

The high spatial density of massive star formation in mergers and starburst galaxies (e.g. Acciari et al. 2009; Acero et al. 2009 creates regions of extremely high cosmic ray energy density, up to about ten thousand times that in the Milky Way Galaxy. Papadopoulos (2010) has proposed that these large energy densities alter the heating rates and ionization fractions in dense gas (n(H2) $> 1 \times 10^4$ cm^{-3}) in the UV-shielded cores that contain much of the molecular gas in these galaxies, so that these cosmic ray dominated regions (CRDRs) have different initial conditions for star formation (Papadopoulos, 2010; Papadopoulos et al., 2011). Papadopoulos (2010) has suggested several possible chemical signatures, but it seems necessary to make a fairly complete and self-consistent thermal/chemical model of dense gas subjected to very high fluxes of cosmic rays. Here, it was necessary to reverse that procedure and to compute the variation of the chemistry as the ionization rate is increased. Lepp & Tiné (1998) made such a calculation

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and computed the chemistry in dense gas subjected to ionization rates varying over a wide range. However, their calculation was for a fixed temperature. Later, Spaans & Meijerink (2005), and Meijerink et al. (2006) concentrated on a restricted chemical network with enhanced ionization rate. Recently, Bayet et al. (2011b) compared the computed chemistry for a large network of 131 species connected in 1700 reactions for many ionization rates from Milky Way values up to about one million times larger. We present a summary of the results obtained for this theoretical study in Section 2 followed by a more dedicated modelling work (Bayet et al., 2010) whose results are compared to subsequent molecular observations in the Perseus Cluster (see Section 3 and Bayet et al. 2011a). The comparison between models and observations has enabled us to constrain for the first time the most likely heating mechanism seen in the filamentary structures of the Perseus Cluster.

2. Theoretical results

Using the UCL-PDR code, we have investigated the sensitivity of the chemistry to variations in the cosmic ray ionisation rate ranging from $\zeta = 2 \times 10^{-17}$ s^{-1} to 1×10^{-12} s^{-1} (see Bayet et al. 2011b). Except for the metallicity which we varied (0.1, 1 and 4 $z_\odot$) all the other parameters such as the gas:dust mass ratio, H_2 formation rate, initial elemental abundances, grain size and albedo, etc., were kept constant at their Milky Way standard values (see for details Bayet et al. 2011b). The gas density and the FUV radiation field were set to $10^4 cm^{-3}$ and 1000 Habing, representing typical conditions the star-forming gas experiences, especially in external galaxies. We studied in particular three regions of visual extinction (A_v =3, 8 and 20 mag), intended to represent translucent, extended molecular and denser molecular material, respectively. We obtained the following conclusions: ***i)*** The dense gas kinetic temperature in galaxies with high cosmic ray ionisation rates is elevated above Milky Way values, and reaches values $\geq$ 3000 K for ionisation rates of about 10^{-12} s^{-1}; ***ii)*** Many potential molecular tracers such as CN, C_2H and HCO^+ can be identified for dense gas in external galaxies in which the cosmic ray ionisation rates are enhanced, even up to rates as large as 10^{-13} s^{-1} (see fractional abundances of about 20 species as a function of ζ for A_v =8 mag in Fig. 1); ***iii)*** For galaxies with ionisation rates as large as 10^{-12} s^{-1}, gas of number density of 10^4 cm^{-3} is largely neutral and atomic, with a minor component of ions. Potential tracers of such gas are rare, but include molecular tracers OH and OH^+ and atomic tracers C and C^+; ***iv)*** Model results for the abundances of various molecular ions detected recently in the Milky Way and in external galaxies appear to be reasonably consistent with an origin in regions of enhanced cosmic ray flux; ***v)*** If CRDRs are also regions of intense radiation fields, then translucent regions are chemically poor relative to regions that are more optically thick; ***vi)*** For regions with $A_v \gtrsim$ 8 mags, the chemistry appears to be independent of depth; ***vii)*** The non-linear dependence of chemistry on metallicity may allow determinations of metallicity through molecular observations.

3. Determination of the heating mechanism in the Perseus Cluster

NGC 1275 in the Perseus cluster contains an AGN and is surrounded with filaments observed in optical, X-ray and IR wavelengths. The interaction of the AGN-driven gas with the accreting material generates turbulence and dissipative waves, and accelerates cosmic rays ionising the filamentary regions. Models from Ferland et al. (2009) concluded that heating rate due to dissipation or cosmic ray induced ionisation is about four order of magnitude higher in NGC1275 than in the local ISM. Whether the interaction of the AGN-driven outflow with obstacles, such as accreting clouds associated with filaments, influences the physical and chemical conditions in the millimeter and submillimeter emission regions to the same extent as in the filamentary optical and infrared emission regions remains an open question.

From recent material, we have been able to estimate the total column densities of CN,

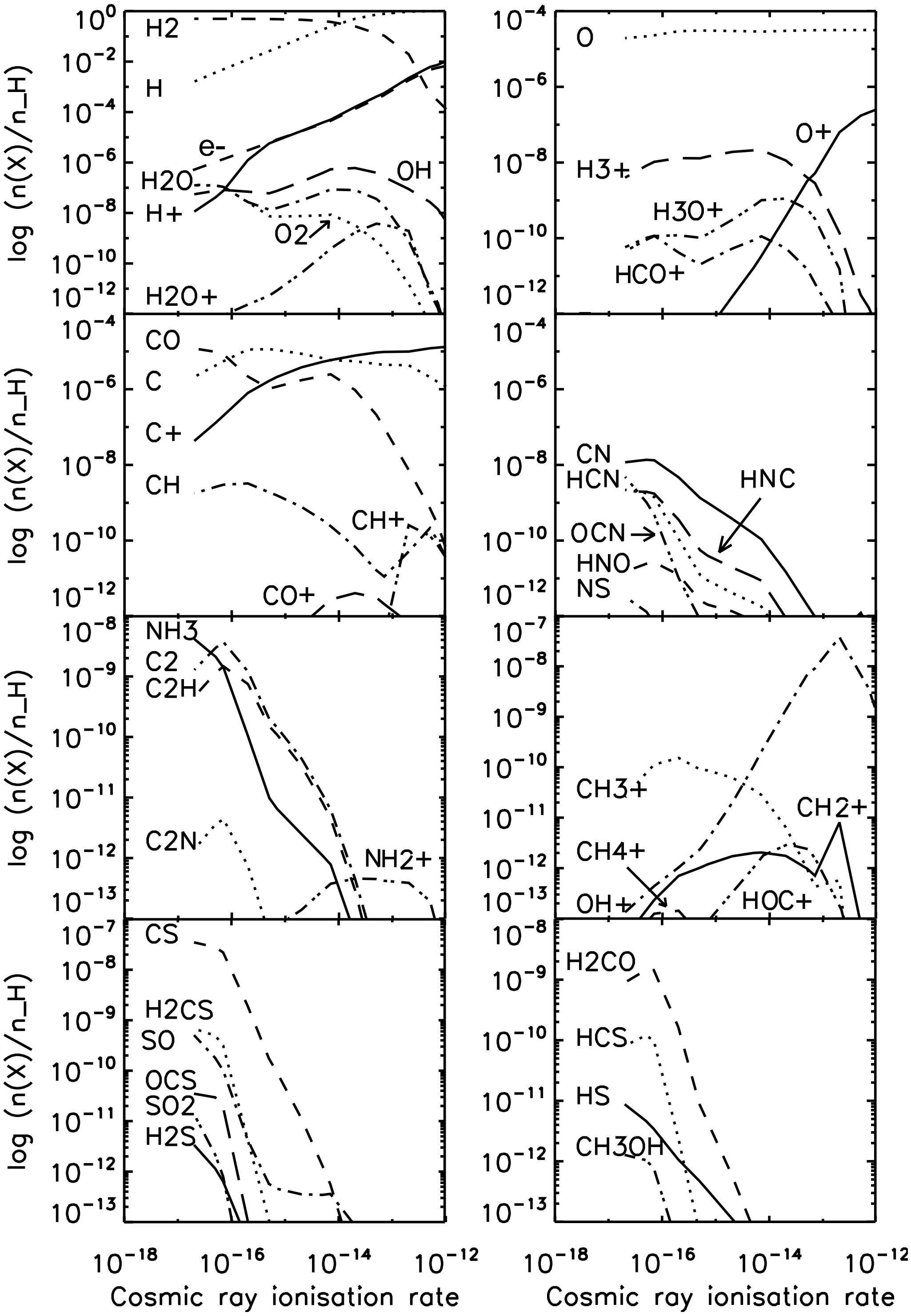

Fig. 1. Fractional abundances ($n(X)/n_H$) of species X in logarithmic scale where n_H is the total number of hydrogen atoms, obtained for the models with a metallicity of 0.1 $z_\odot$ for an A_v of 8 mag as functions of cosmic ray ionisation rate (ζ) in s^{-1}

C_2H and HCO^+ in both central and filamentary regions and compare them to those predicted by models. Indeed, Bayet et al. (2010) produced the first chemical models for molecular millimeter and submillimeter emission line regions like those surrounding NGC1275, and showed that HCO^+, C_2H and CN are particularly suitable since they remain abundant even as some other species decline in abundance as the cosmic ray ionisation and heating rate rise. The value of CS and SO emissions as diagnostics has, however, been shown as compromised by the uncertainty associated with sulphur depletion (e. g. Ruffle et al. 1999 and references therein).

To summarize the results of the comparison between models and observations, we explain the CN, C_2H and HCO^+ observed column densities with one model (Model E in Bayet et al. 2011a) that has a high cosmic ray ionisation rate (i.e. $5 \times 10^{-15}s^{-1}$) and a low additional heating source (i.e. $\leqslant 1 \times 10^{-22}$ergcm^{-3}s^{-1}) in both regions of the Perseus cluster. From our analysis, there is thus a unique combination of physical conditions which reproduces the estimates of column densities derived from the observations within a factor of 5 or less. Temperatures under such physical conditions are estimated to be ranging from 40 K to 60 K, depending on the optical depth, assuming that the gas number density is fixed at 10^4cm^{-3}. In such environments, we predict that the HCO^+ and the CN are likely produced in the external layers of the molecular region, i.e. in regions where the average A_v= 3 mag, where FUV photons are of importance in the regulation of the chemistry.

4. Conclusions

We have presented here the set of molecular tracers for CRDRs as a function of the cosmic-ray ionisation rate. This study has been applied to the determination of the origin of the heating mechanism in the Perseus Cluster. It is clear from this work that cosmic ray play a fundamental role in processes related to star formation in external galaxies.

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