First maps of cosmic-ray ionization rate in high-mass star-forming regions with ALMA

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1. Introduction

Under typical dark cloud conditions, low-energy (< 1 TeV) cosmic rays (CRs) are the primary ionising agent for the interstellar medium, determining the gas chemical composition and drastically influencing the formation of stars and planets. However, under the same conditions, reliable estimates of the cosmic-ray ionisation rate relative to H_2 ($\zeta^{\rm ion}_{\rm H_2}$) are often difficult to obtain, and $\zeta^{\rm ion}_{\rm H_2}$ is strongly influenced by the model assumed. Recently, a new analytical approach to estimate $\zeta^{\rm ion}_{\rm H_2}$ in the densest regions of molecular clouds was proposed by Bovino et al. (2020) and applied by Sabatini et al. (2020) in the context of high-mass star formation. The aforementioned method is model-independent and based on the estimate of the H_3^+ column density using its deuterated forms (such as H_2D^+) which are known to be very abundant in dense and cold star-forming regions. This poster presents the first high-resolution maps of $\zeta^{\rm ion}_{\rm H_2}$ in two massive clumps where multiple cores of ortho-H_2D^+ were observed taking advantage of the exceptional observational capabilities of ALMA (Redaelli et al., 2021).

2. Methodology and Analysis

The method proposed by Bovino et al. (2020) is based on the following analytical formulation

$$\zeta^{\rm ion}_{\rm H_2} = k_{\rm CO}^{\rm o\text{-}H_3^+} \frac{X({\rm CO})\, N({\rm o\text{-}H_2D^+})}{3\, R_{\rm D}\, \ell}, \qquad (1)$$

where $k_{\rm CO}^{\rm o\text{-}H_3^+}$ is the rate at which CO destroys o-H_3^+, X(CO) the abundance of CO relative to H_2, $R_{\rm D}$ is the deuteration of HCO^+ ($R_{\rm D} = DCO^+/HCO^+$), ℓ is the path length over which the column densities are estimated, and N(o-H_2D^+) is the column density of the main H_3^+ isotopologue. The robustness and reliability of the method have been recently confirmed by Redaelli et al. (in prep.), finding an accuracy of a factor of 1.5-3.

- ✎ We targeted AGAL351.571+00.762 (hereafter AG351) and AGAL354.944-00.537 (AG354), which belong to ATLASGAL (Schuller et al., 2009);
- ✎ Available observations of o-H_2D^+ ($1_{1,0} - 1_{1,1}$) by Redaelli et al. (2021), plus new DCO^+(3-2), $C^{18}O$(2-1) and $H^{13}CO^+$(3-2) data distributed into two ALMA (12m+7m+TP) spectral setups (angular scales from ∼0.7″ to ∼32″);
- ✎ Column densities of all the molecular species following Sabatini et al. (2022), assuming LTE and optical depth effects ($\tau < 1.1$);
- ✎ Figure 1 summarises how the parameters entering Equation 1 are distributed in each core;

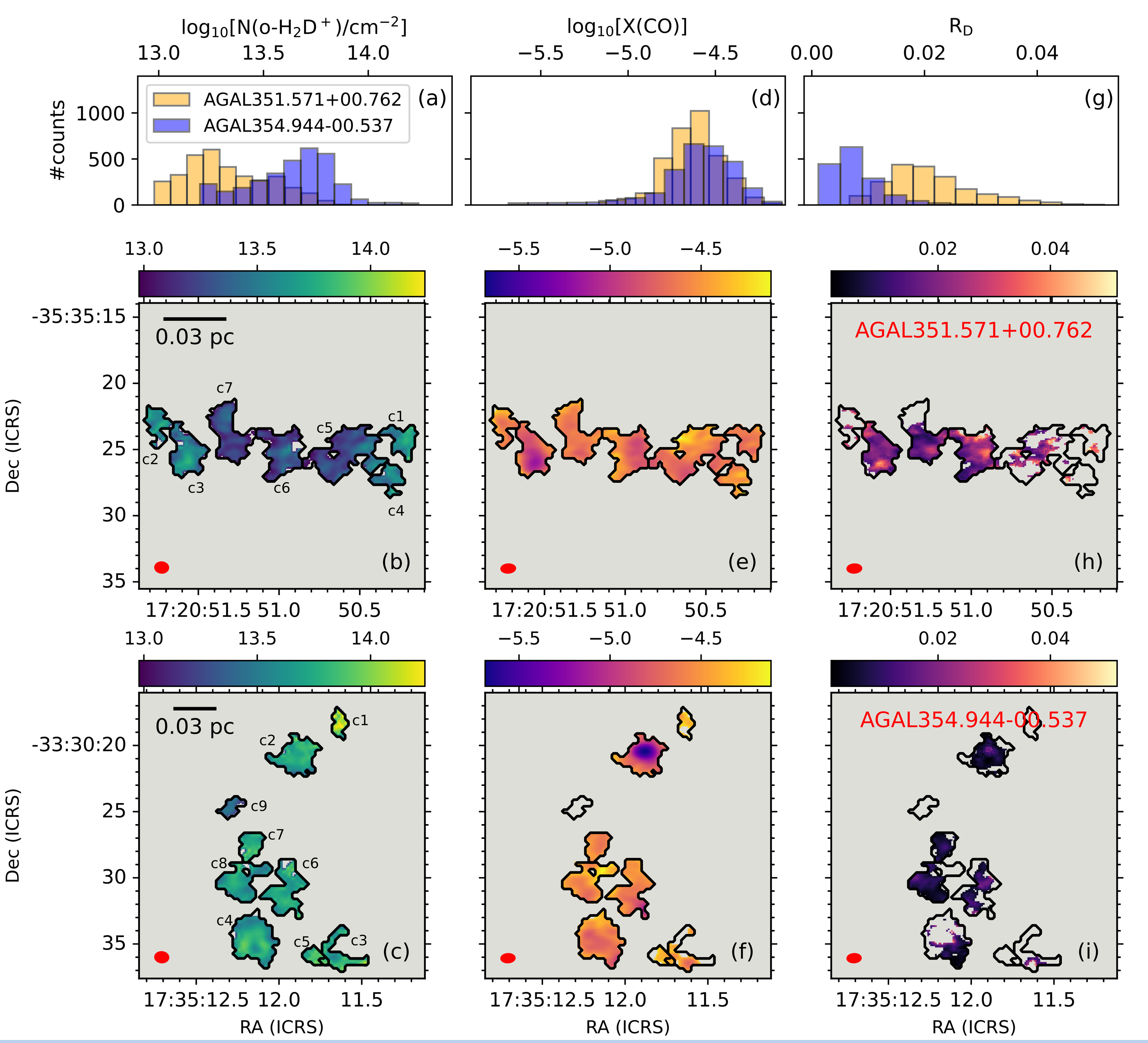

Figure 1: (a,b,c) $\log_{10}[N({\rm o\text{-}H_2D^+})/{\rm cm^{-2}}]$, (d,e,f) $\log_{10}$[X(CO)]; (g,h,i) $R_{\rm D}$ derived for AG351 and AG354, respectively. Cores' IDs from Redaelli et al. (2021).

3. Results

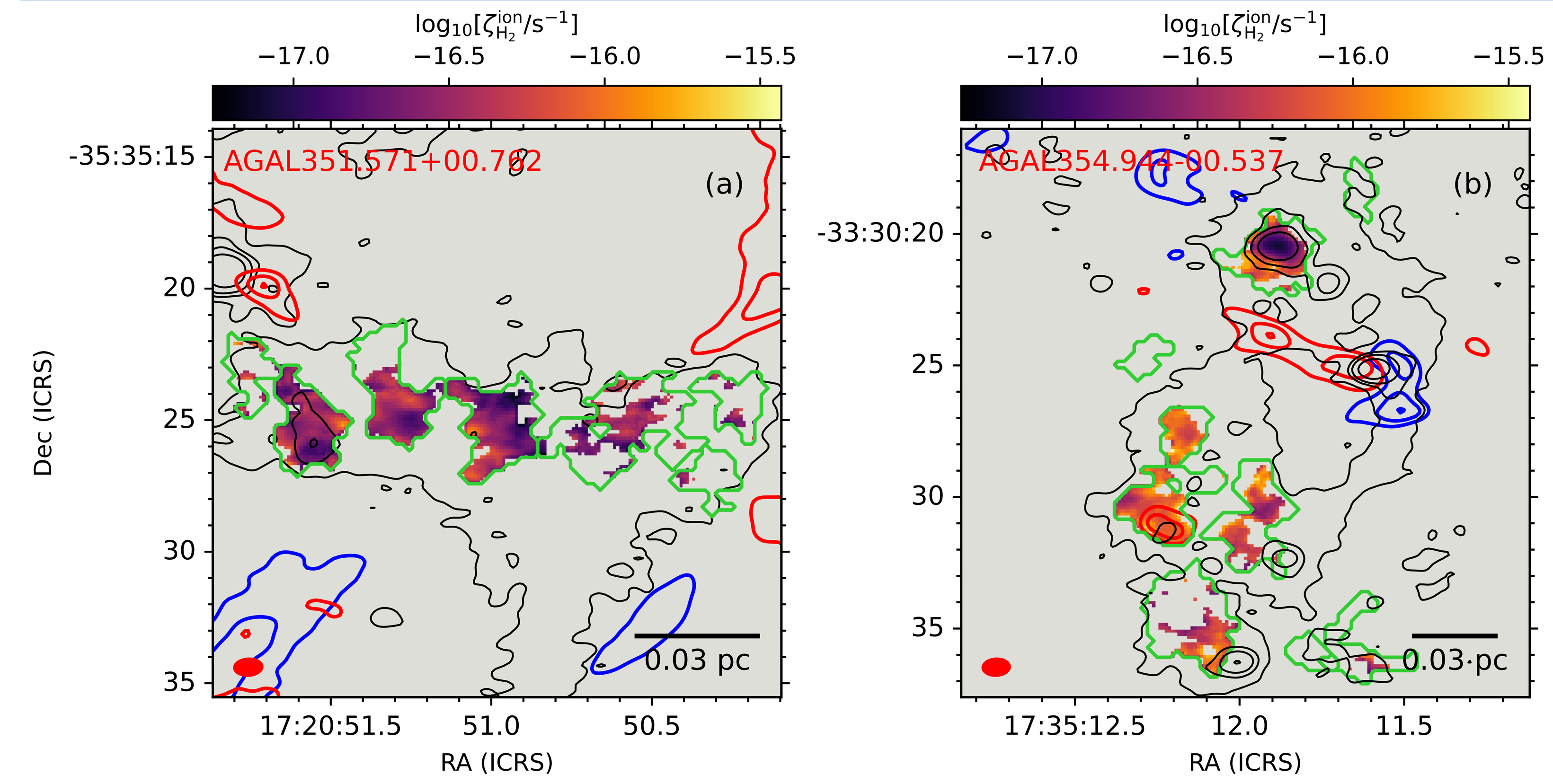

Figure 2: Map of the $\log_{10}(\zeta^{\rm ion}_{\rm H_2}/s^{-1})$ derived for AG351 (a) and AG354 (b). The black contours show the ALMA continuum at 1.33 mm (levels: $[3, 6, 9, 15, 30]\sigma$, with $1\sigma = 0.1$ mJy beam^{-1}). The blue- and red-shifted components of $^{12}C^{16}O$ (2-1) emission are shown as blue and red contours.

- ✎ Figure 2 provides the first look at the $\zeta^{\rm ion}_{\rm H_2}$ distribution in two intermediate-mass star-forming regions observed at the remarkable angular resolution of ALMA;
- ✎ Final uncertainties on the $\zeta^{\rm ion}_{\rm H_2}$ smaller than a factor of 2;
- ✎ Figure 3 summarises the $\zeta^{\rm ion}_{\rm H_2}$ obtained for a sample of high- and low-mass star-forming regions. We assumed a conservative error of 20% in $N(H_2)$;
- ✎ Line profiles are the models by Padovani et al. (2022) considering different slopes for the CR proton spectrum;

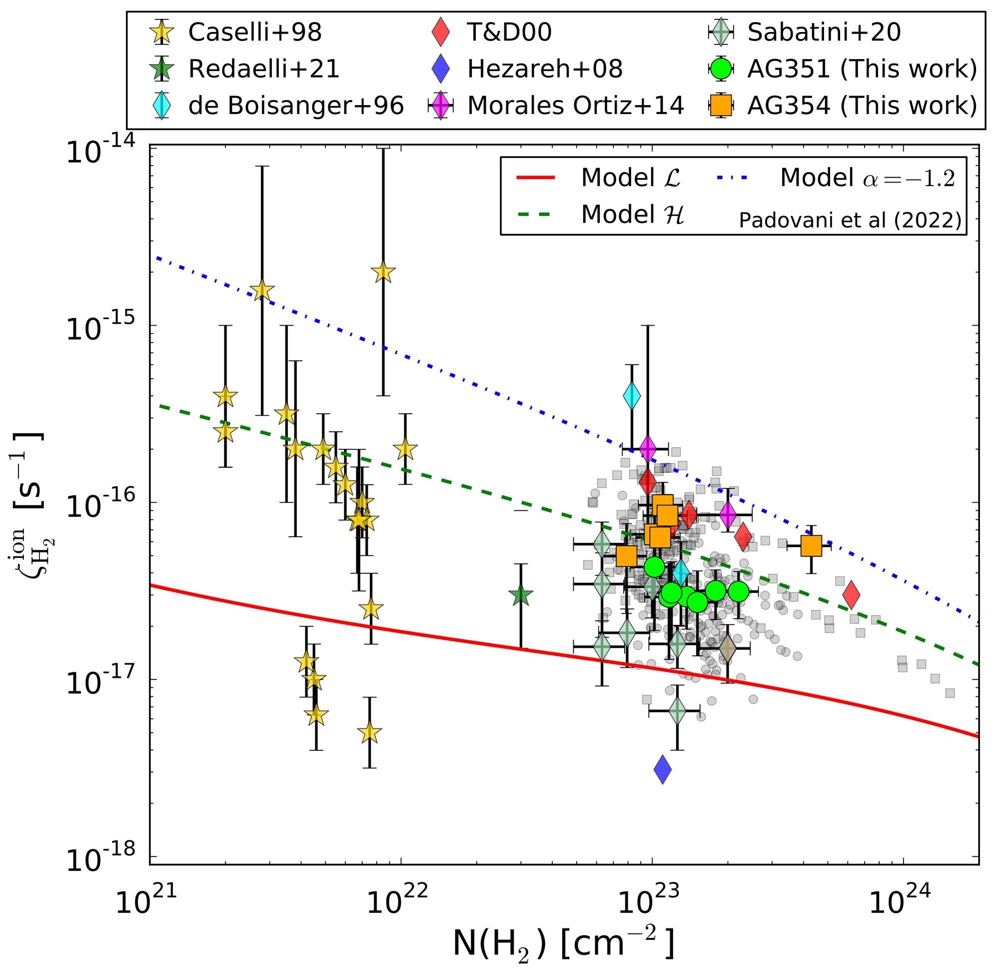

Figure 3: Estimated $\zeta^{\rm ion}_{\rm H_2}$ vs $N(H_2)$ for a sample of low- and high-mass star-forming regions. Grey circles and squares refer to the $\zeta^{\rm ion}_{\rm H_2}$ in each resolution element in Figure 2, whilst green circles and orange squares are the average values for each core identified in o-H_2D^+.

4. Conclusions

- ✎ We obtain $\langle\zeta^{\rm ion}_{\rm H_2}\rangle$ that span from 3×10^{-17} to 10^{-16} s^{-1}, depending on the different distribution of the main ion carriers (Figure 1);
- ✎ The cores belonging to the same parental clump show comparable $\zeta^{\rm ion}_{\rm H_2}$, suggesting that the ionisation properties of prestellar regions are determined by global rather than local effects (Figure 2);
- ✎ The scatter of $\zeta^{\rm ion}_{\rm H_2}$ values derived at a given $N(H_2)$ could reflect a different morphology of magnetic fields that will be investigated in the near future thanks to the increasing capabilities of modern astronomical facilities, e.g. ALMA, in polarisation observations (Figure 3);

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