A high-resolution study of the CO-to-H_2 conversion factor across the Perseus molecular cloud: Confronting theory with observations

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The formation of dense molecular gas out of the diffuse interstellar medium is a critical step toward star formation. Yet, the fundamental assumptions made by traditional models of the formation of molecular gas, e.g., steady state and time-independent chemistry, have been largely untested. To address this issue, we derive the CO-to-H_2 conversion factor, X(CO) = N(H_2)/I(CO), across the Perseus molecular cloud on ~0.4 pc scales and compare results with two contrasting models, a one-dimensional photodissociation region (PDR) model by Wolfire et al. (2010) and a three-dimensional magnetohydrodynamic (MHD) model by Shetty et al. (2011). We estimate an average X(CO) ~ 3×10^{19} cm^{-2} (K km $s^{-1})^{-1}$ and find that a factor of ~7 discrepancy between our estimate and the canonical value in the Milky Way primarily results from different methodologies to derive X(CO). In addition, we show that X(CO) varies by a factor of ~100 within the sub-regions in Perseus, suggesting that X(CO) strongly depends on local conditions in the interstellar medium. The PDR model is in excellent agreement with the observed N(HI), N(H_2), I(CO), and X(CO) distributions but requires a large diffuse HI halo. The MHD model reproduces our data reasonably well, implying that time-dependent effects on H_2 and CO formation are insignificant for evolved molecular clouds like Perseus. However, we find interesting discrepancies, e.g., a broader range of N(HI), likely underestimated I(CO), and a large scatter of I(CO) at small column density regions. These discrepancies likely result from strong compressions/rarefactions and large density inhomogeneities in the MHD model.