The role of Cosmic Rays and Optical Light in Powering Line Emission from CO molecules in Molecular Clouds

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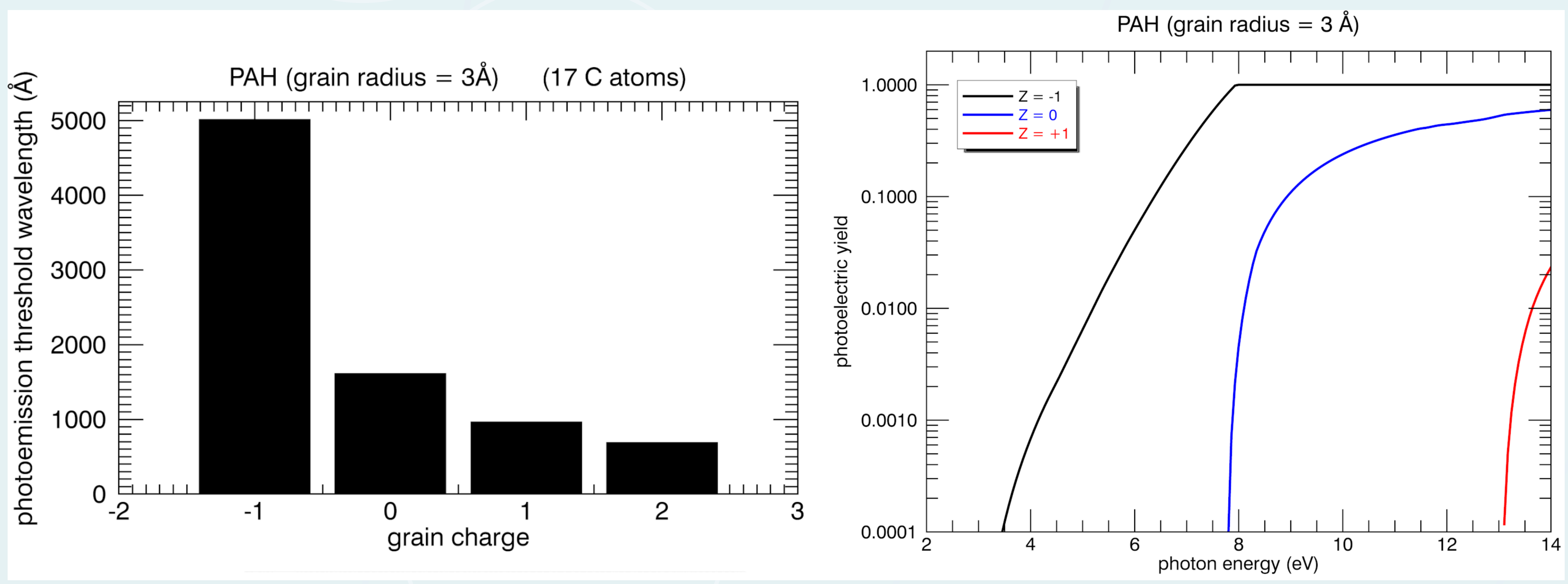
Abstract

One of the most important tracers of molecular hydrogen (H_2) gas in spiral galaxies is line emission from transitions between rotational levels of the vibrational ground state of the CO molecule, in the millimetric to FIR spectral range. This line emission is however also an important cooling channel for gas in opaque clouds, and moreover, such clouds host almost all the H_2 gas under the physical conditions prevalent in the disks of local Universe spiral galaxies. This being the case, an accurate determination of the mass of H_2 from observations of the rotational CO lines requires an absolute knowledge of the gas heating in opaque clouds. In this work, we utilise simple semi-analytic models for interstellar clouds to quantify at the microscopic level interstellar competing mechanisms for the latter, including photoelectric (PE) heating from photelectrons ejected from dust grains, heating by cosmic rays (CRs), and collisional heating by dust grains. Most particularly, we interface the PE heating model of Weingartner & Draine (2001) to UV-optical radiation fields of arbitrary amplitude and colour to consider the potential role of the heating of gas by optical light from the ambient diffuse interstellar radiation field (ISRF) in which the clouds are situated. We find optical heating, together with CR heating, can significantly power CO line emission in molecular clouds which are "passive", in the sense that they have not yet started to form stars. In addition to direct heating of gas by CRs, we also identify and quantify a "catalytic" effect of CRs on the optical PE heating, whereby the efficiency of the latter is enhanced by the additional negative charge on grains induced by CR ionisation of the gas. The model is applied to the interpretation of the CO line emission from passive clouds from the nearby spiral galaxy NGC 628, using data from PHANGS-ALMA and PHANGS-JWST in conjunction with large scale radiative transfer modelling of the ISRF in that galaxy.

A Photoelectric heating of interstellar gas

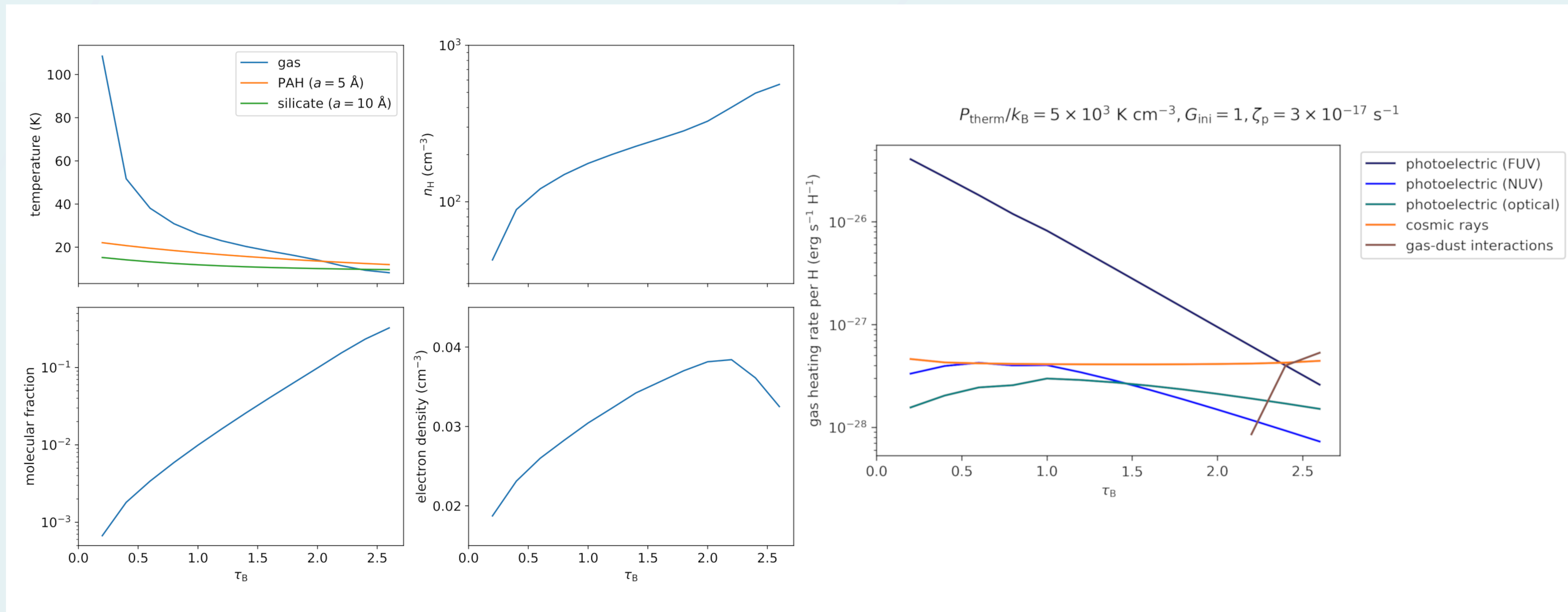
- Photoelectrons emitted following the photoionisation of grains/large molecules are predicted to dominate the heating of interstellar gas
- Heating efficiency depends on grain charge and composition, as well as strength and colour of the interstellar radiation field
- Heating is sensitive to the abundance of small, negatively charged grains and molecules



Wong & Tuffs (in preparation)

B Slab calculations using the Mathis et al. (1983) ISRF

We carry out calculations of the thermal and chemical structure of hypothetical slabs illuminated by various external interstellar radiation fields (ISRF) found at different locations in the disks of spiral galaxies, and with a fixed ambient pressures also representative of those expected in spiral galaxies. The example shown here is for an external radiation field typical in the solar neighbourhood (Mathis et al. (1983) ISRF with a galactocentric radius of 8 kpc) and at a fixed thermal pressure of $5 \times 10^3\, k_B$ K cm^{-3}. Gas heating due cosmic rays and due to gas-dust interactions are comparable to the gas heating rate by the ISRF due to photoelectric effect on dust grains by FUV photons at a B-band optical depth of 2.5, the point at which transition from neutral to molecular hydrogen starts. Optical photons (via PE heating) have a non-negligible contribution to the gas heating rate at this optical depth.



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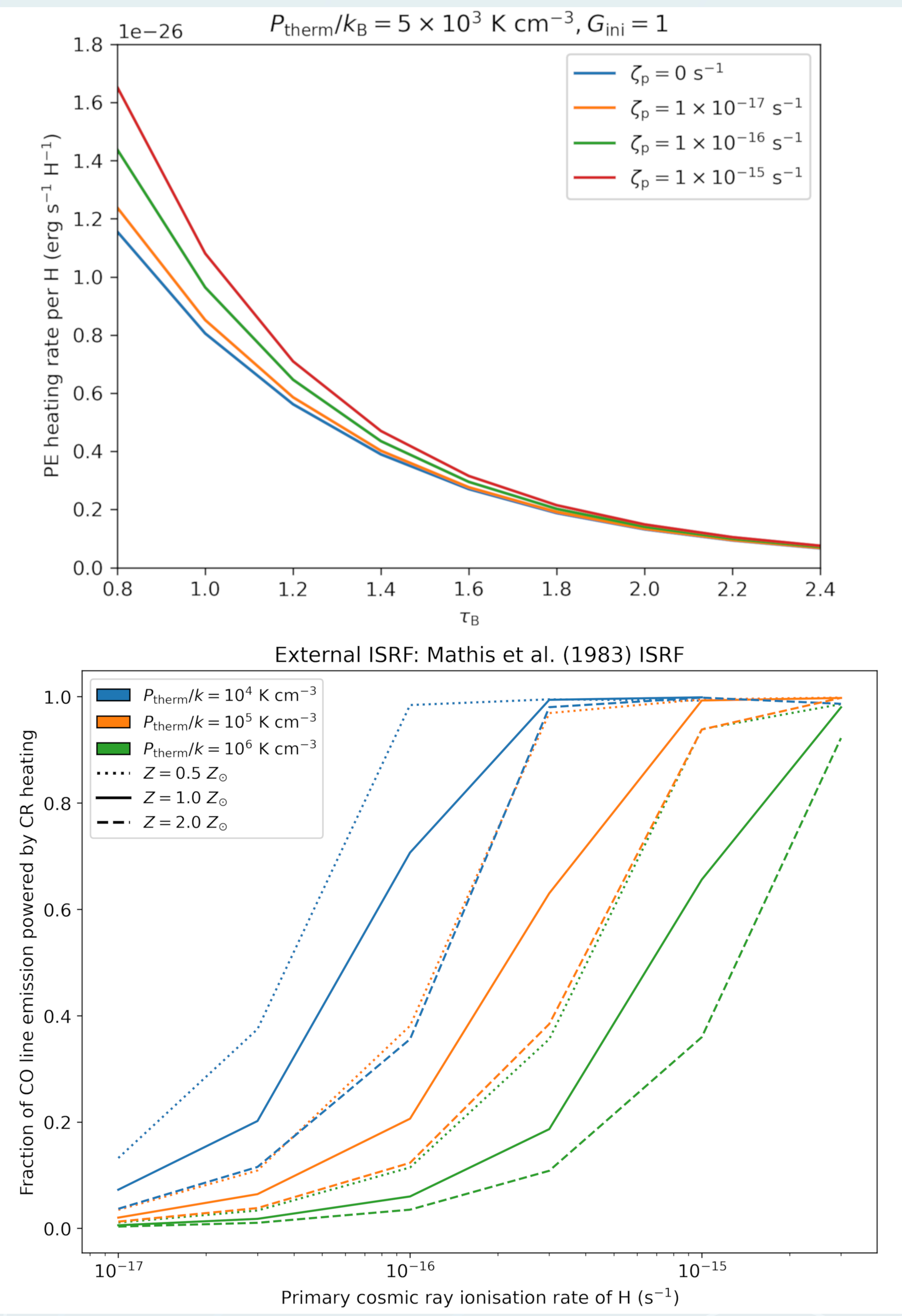
C The "catalyst" effect and the importance of cosmic rays in driving CO line emission

We find that high cosmic ray ionisation indirectly boosts photoelectric heating by lowering the charges of dust grains with the free electrons produced in the ionisation of gas particles (upper panel). This "catalyst" effect of cosmic rays is stronger when the UV/optical radiation field is relatively weak. We also quantified the fraction of gas heating due to CRs. In particular, we calculate the fraction of CO line emission that is powered by CRs (lower panel) as a function of CR ionisation rate. The threshold CR ionisation rate for which this fraction becomes significant is a strong function of both pressure and metallicity.



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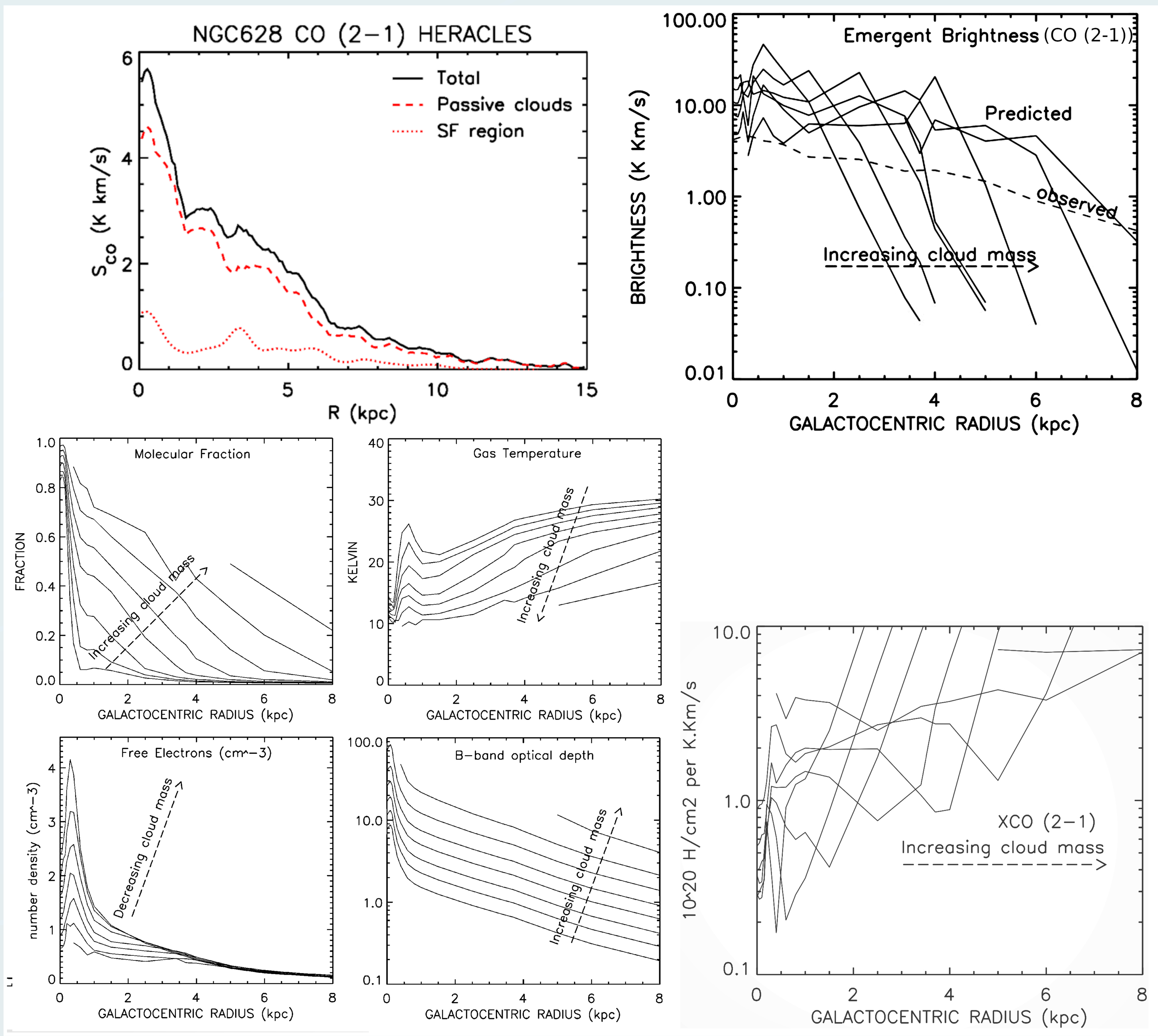
D Predicted CO (2-1) emission from NGC 628

We tested the hypothesis that the line emission in the passive clouds was powered by the ambient diffuse ISRF using a simple semi-analytic model for the structure of virially supported clouds in combination with a self-consistent analysis of the radiative transfer (RT) of starlight in spherical symmetry and the emitted line emission in the cloud as predicted by the chemical reaction network. This model predicts the transition from neutral to molecular gas as a function of B-band optical depth in clouds. The top LH panel shows the observed brightness of the pure rotational (2-1) line of the CO molecule in its main isotopes as a function of galactocentric radius, using publically available ALMA data from Leroy et al. (2021). Components from passive- and actively star-forming clouds were separated on the basis of the warm dust emission from clouds, as traced using publically available continuum emission at 21 µm measured by JWST.

The comparison between observed and predicted brightness in the CO (2–1) line is shown in the top RH panel for assumed cloud masses of [30 $M_\odot$, 100 $M_\odot$, 300 $M_\odot$, 1000 $M_\odot$, 3000 $M_\odot$, 10000 $M_\odot$]. The primary CR ionisation rate of H is fixed at 3×10^{-17} s^{-1}. The ambient ISRF incident on clouds is taken from the large scale axisymmetric RT model of Rushton et al. (2022). The model predicting CO line brightness thus combines large-scale (up to $\simeq$10 kpc) and small scale RT calculations (down to $\simeq$0.1 pc) within clouds. In this scheme, the large scale RT calculations also predict the ambient pressure of the ISM in which clouds are situated, as well as the total molecular gas mass as derived from the subtraction of the observed H I gas surface density from the total gas surface density derived from the dust emission.

The model overpredicts the surface surface of CO emission by factors of 2–3. This likely indicates that the emissivity of dust grains in the molecular medium in clouds (for which we have used the Weingartner & Draine (2001) grain model) is underestimated by at least a factor of 2–3. Properties of passive clouds of different cloud mass are predicted to vary strongly with galactocentric radius due to the dependencies of ambient pressure and ISRF on location (lower LH panels). We predict the X_{CO} factor for the CO (2–1) line as a function of galactocentric radius and cloud mass (lower RH panel), also showing systematic trends with galactocentric radius.



Rushton, Wong & Tuffs (in preparation)

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