Determining the cosmic-ray flux in the Milky Way and nearby galaxies

1. **Science aim/goal:** To provide unique measurements of the flux of low-energy cosmic-rays throughout the Milky Way, and in nearby galaxies, by surveying hydride molecular ions in the ISM.

2.

(i) Scientific Importance:

Low-energy cosmic-rays (CR) control the heating, ionization and chemistry of dense molecular clouds. As such, CR set the initial conditions for star formation; while their production – e.g. in supernova remnants (SNR) – is associated with stellar death. By determining the abundances of specific molecular ions within a large sample of molecular clouds, we can determine the cosmic-ray ionization rate (CRIR*) and its variation* in the Milky Way and in nearby galaxies. Such a determination will address several key questions, including: (1) what is the typical CRIR as a function of Galactocentric distance? (2) how much does the CRIR vary from one molecular cloud to another? (3) to what extent are CR excluded from dense molecular clouds? (4) what are the sources (e.g. SNR) of low-energy CR?

(ii) Measurements Required:

High-resolution absorption-line spectroscopy of specific molecular transitions in the 0.5 – 2 THz spectral range is needed along sight-lines toward a large sample of submillimeter continuum sources. Such measurements will provide the column densities of ArH^+, OH^+, H_2O^+, H_2O and H_3O^+ – all of which are produced via reaction sequences initiated by the CR ionization of H or H_2 – together with the column densities of CH and HF, which provide estimates of the H_2 column densities. Interpreted in the context of astrochemical models, such measurements of multiple hydride molecular ions will allow the CRIR to be probed in clouds of varying molecular fraction. In addition, we will determine the relative populations of several metastable states of H_3O^+, providing additional constraints on the H_3O^+ formation rate (Lis et al. 2014) and thus the CRIR.

(iii) Uniqueness to 10μm to few mm wavelength facility:

While high-energy (E > 280 MeV) cosmic-rays can be probed using gamma-ray observations, submillimeter observations of molecular ions provide a unique probe of the low-energy CR that control the heating and ionization of star-forming molecular clouds. In the Galactic Center and the vicinity of the Sun, ground-based near-IR observations of the H_3^+ molecular ion provide a complementary probe of the CRIR. However, whereas extinction in the Galactic disk severely limits near-IR measurements, submillimeter observations can be performed toward background sources at large distances within the disk.

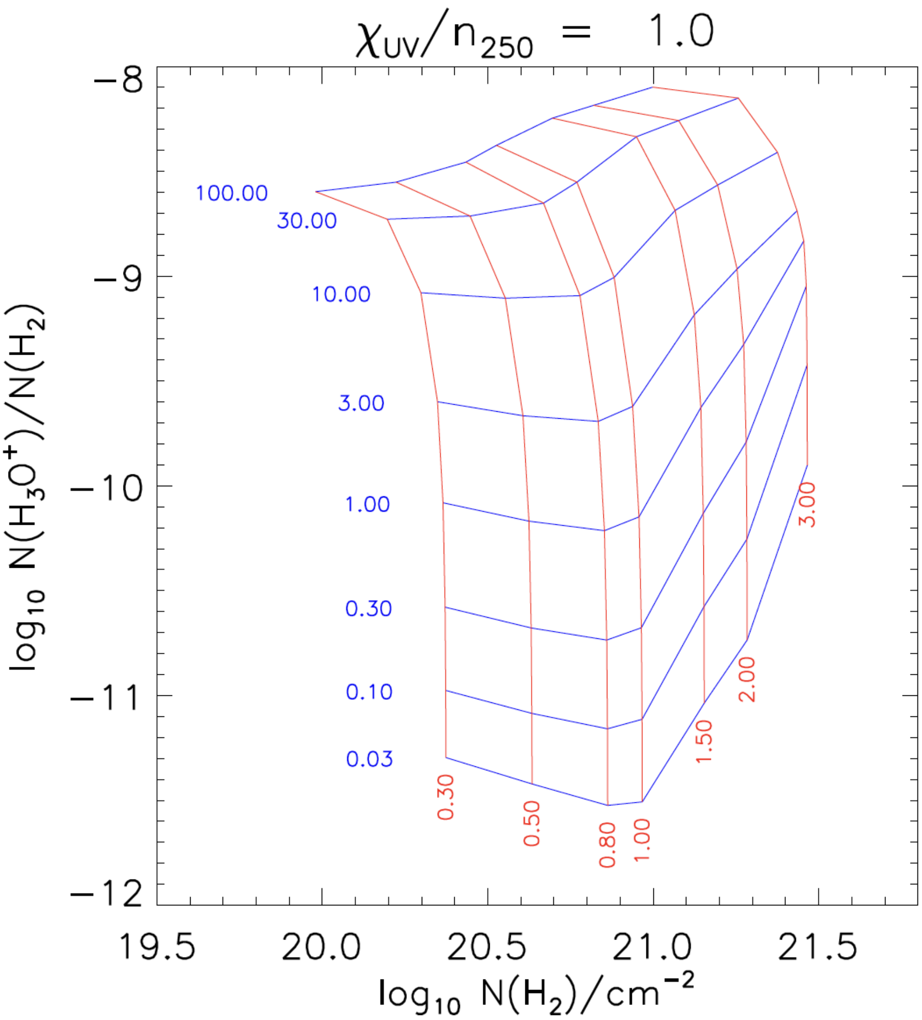
(iv) Longevity/Durability:

All absorption lines of H_3O^+ and H_2O are completely inaccessible from the ground, as are the strongest transitions of OH^+ and H_2O^+; ground-based observations of ArH^+ are severely limited by atmospheric absorption. Some of the required transitions are detectable with SOFIA, but the much smaller collecting area (factor of 13) would make a systematic survey prohibitively time-consuming. (For example, a 200 hour OST key program would require at least 2600 hours of SOFIA time, corresponding to ~ 5 years of SOFIA operations at a cost of $400M). Previous *Herschel* observations of ArH^+, OH^+ and H_2O^+ have provided a proof of concept (Neufeld & Wolfire 2017; NW17); an OST survey would greatly extend the reach of NW17 to fainter background sources, including targets in the outer Galaxy and beyond.

Table

Parameter	Unit	Required value	Desired Value	Comments
Lines of ArH^+,OH^+, H_2O^+, H_3O^+, H_2O (all pure rotational lines with the lower level being the ground state or a metastable state)	GHz	617, 971, 985 1113/1115, 1232, 1655, 1663, 1712, 1808, 2007/2011		Most lines are expected to be detected in absorption. Some sources will also show emission lines
Number of targets		~ 100	500	The PACS point source catalog contains ~ 1000 sources of the required flux (> 160 Jy at 1.8 THz)
Survey area	deg.^{2}	N/A	N/A	
Angular resolution	arcsec	5 to 15		Not critical for absorption
Spectral resolution	k[illegible]	0.3 to 1	0.1	Resolve line profile (source dependent)
Bandwidth	k[illegible]	1000	5000	Larger values needed for the Galactic Ctr. or SNR shocks
Continuum Sensitivity (1 σ)	μJy	N/A	N/A	
Spectral line sensitivity (1 σ)	mK in a 1 km/s channel	30		For absorption, the requirement is 1% of the continuum in a 1 km/s channel for a 160 Jy source
Signal –to-noise		100		
Dynamic range				
Field of Regard				
Cadence (*observable sky during mission)*				
Any other requirement				
Heterodyne Rx specific questions:				
Required Tuning range (Dopplershift)	*km/s*	*-2000 to +10000*		
Dual frequency requirement?		*No*	*Yes*	
Polarization Normally we will observe one linear polarization, does the orientation matter for your science?		*No*	*No*	
Polarization measurements required?		*No*	*No*	
Off position requirements: Fixed throw, or dedicated off?		*Fixed*		*Dual beam switching for accurate continuum measurement*
if fixed throw, minimum distance	*arcmin*	*3 to 5*		

Figure:



Example predictions for the H_3O^+ abundance in diffuse molecular clouds, based on the model of Neufeld & Wolfire (2017). H_2 column densities and N(H_3O^+)/ N(H_2) column density ratios predicted for diffuse molecular clouds, with contours of visual extinction, A_V (in mag), shown in red, and contours of CRIR shown in blue (in units of 10^{-16} primary H ionizations per s). The H_3O^+ abundance is an increasing function of the CRIR.

5. Key references:

Grenier, I. A., Black, J. H., Strong, A. W. 2015. *The Nine Lives of Cosmic Rays in Galaxies.* ARAA, 53, 199

Gerin, M., Neufeld, D. A., Goicoechea, J. R. 2016. *Interstellar Hydrides.* ARAA, 54, 181

Lis, D. et al. 2014. *Widespread Rotationally Hot Hydronium Ion in the Galactic Interstellar Medium.* ApJ, 785, 135.

Neufeld, D. A., & Wolfire, M.G. 2017. *The cosmic ray ionization rate in the Galactic disk, as determined from observations of molecular ions*. arXiv:1704.03877.

6. Class your science in at least one of the 4 overall topics

- Unveiling the Growth of Black Holes and Galaxies over Cosmic Time