Onsala Proposal

Tan **0108.F-9310**

The Timescale of Star Formation - Astrochemical ages from ortho- and para- H2D+ (resubmission of accepted project 107.F-9309A)

Semester: may2021 **Science Cat.: ISM and star formation**

Abstract

The timescale of star formation is of fundamental astrophysical importance but is currently very uncertain. The discovery of para-H2D+ with SOFIA-GREAT and the comparison of its line strength with that of ortho-H2D+ observed by APEX in the accretion envelop of a forming Sun-like star (Brunken et al. 2014, Nature, 516, 219) and the fact that the ortho-to-para ratio (OPR) of H2D+ can be used as a proxy of the OPR of H2, which is the best chemical clock of molecular clouds, enabled an age estimate of at least one million years for this source. This ground-breaking result has motivated follow-up studies with SOFIA-GREAT to measure para-H2D+ in a larger number of protostars from the SOMA survey. Here we propose to observe 6 selected high priority relatively cool and/or early-stage objects with APEX to measure ortho-H2D+, which is necessary to derive their OPR ratios and thus extend these astrochemical timescale studies to a larger number of sources and environments.

Applicants

Name	Affiliation	Email	Country		Potential observer
Mr. Chi Yan Law	Chalmers University of Technology (Space, Earth and Environment)	chiyan.law@chalmers.se	Sweden		Yes
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Jorma Harju	University of Helsinki (Department of Physics)	jorma.harju@helsinki.fi	Finland		
Prof. Ke Wang	Kavli Institute for Astronomy and Astrophysics, Peking University	kwang.astro@gmail.com	China		
Yichen Zhang	RIKEN	yczhang.astro@gmail.com	Japan		
Chia-Jung Hsu	Chalmers University of Technology (Space, Earth and Environment)	chiajung.hsu@chalmers.se	Sweden		
Dr. Giuliana Cosentino	Chalmers University of Technology (Space, Earth and Environment)	giuliana.cosentino@chalmers.se	Sweden		
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Contact Author

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Is this a long term proposal: No

Overall scheduling requirements

For the source to be above declination 40 deg:

All sources (May-August)

Observing runs

run	telescope	instrument	time request (minimal)	frequency (GHz)	weather (pwv)	LST range	comments/constraints
A	APEX	SEPIA345 (277-371 GHz)	13h (13h)	372.6	0.5-1 mm		

Targets

Source	RA	Dec	Epoch	Vlsr (km/s)	Duration (min)	Runs	Comments
G049.27-00.34	19:23:06.99	+14:20:15.8	J2000	67.4	137	A	Time include overhead
G027.36-00.17	18:41:50.97	-05:01:45.1	J2000	92.0	137	A	Time include overhead
G019.08-00.29	18:26:48.42	-12:26:28.0	J2000	65.4	137	A	Time include overhead
G031.28+00.06	18:48:11.82	-01:26:31.0	J2000	109.0	137	A	TIme include overhead
G028.20-00.05	18:42:58.14	-04:14:04.8	J2000	95.6	137	A	Time include overhead

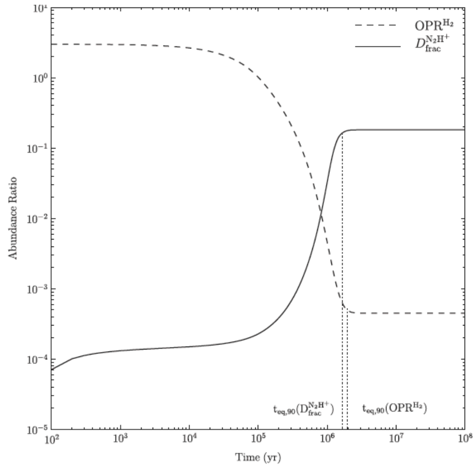
Scientific Rationale

This is a follow-up/re-submission of the approved proposal (107.F-9309(A)) in the last cycle, which was not able to be carried out due to the COVID-19 shutdown.

Background: The timescale of star formation is of fundamental astrophysical importance, but is currently very uncertain and is under active debate. For both individual protostars and entire protoclusters, theoretical models range from those involving fast collapse (e.g., Elmegreen 2007, ApJ, 668, 1064; Hartmann & Burkert 2007, ApJ, 654, 988; Hartmann, Ballesteros-Paredes, & Heitsch 2012, MNRAS, 420, 1457) to those in which star formation proceeds much more slowly due to some combination of magnetic and turbulent support (e.g., Mouschovias, Tassis & Kunz 2006, ApJ, 646, 1043; Tan, Krumholz & McKee 2006, ApJ, 641, L121; Nakamura & Li 2007, ApJ, 662, 395; Da Rio, Tan & Jaehnig 2014, ApJ, 795, 55). Determining the ages of molecular clouds is crucial to put stringent constraints on the dynamical evolution of star-forming regions and discriminate between these models of fast and slow star formation. The only way to measure cloud ages is by observations and chemical modelling of specific molecules that are particularly sensitive to time. In the past several years, it has been shown that deuterated molecules, especially N_2D^+, are excellent chemical clocks (e.g., Pagani et al. 2011, ApJ, 39, L35; Kong, Caselli, Tan et al. 2015, ApJ, 804, 98). The reason for this is that the Deuterium fraction (D_{frac}, defined as the abundance or column density ratio of the deuterated and the hydrogenated form of the same species) increases with time just before star formation, following the steady decrease in the ortho-to-para ratio of H_2 molecules. However, measurements of D_{frac} can have limitations, as the equilibrium value of D_{frac} also depends on several other parameters, such as the gas & dust temperatures, the gas volume density, and the cosmic ray ionization rate. One way to directly trace the OPR of H_2 is to measure the OPR of H_2D^+, as the two are linked by a simple linear relation (Hugo et al. 2007). Brünken et al. (2014, Nature, 516, 219) (see Figure 1) detected for the first time para-H_2D^+ with SOFIA-GREAT and showed that the OPR of H_2D^+ only depends on the OPR of H_2 and the temperature, which can be determined with other methods (in particular using *Herschel* sub-mm dust continuum emission and/or ammonia data). In fact, Brunken et al. (2014) arrived at the most accurate estimate of a molecular cloud core age ($>$ one million years), strongly suggesting that the contraction of the cloud must have happened over a time scale significantly ($> 10\times$) longer that the free fall (dynamical) time scale. This is a very important result, which needs further investigation by significantly enlarging the sample of objects. This is the aim of the current proposal, which complements SOFIA proposals to observe p-H_2D^+ in these same sources.

Source Selection and Observational Plan: Here we have selected a sample of 5 relatively cool and/or early-stage protostars from the SOFIA MAssive (SOMA) star formation survey (De Buizer et al. 2017, ApJ, 843, 33; Liu et al. 2019, ApJ, 874, 16). This survey involves mid-infrared (i.e., $\sim 10\ \mu$m) to far-infrared (i.e., $\sim 40\ \mu$m) observations with SOFIA-FORCAST. Combined with ancillary data from the near IR to the sub-mm, we are able to construct detailed spectral energy distributions (SEDs) and multi-wavelength images of the sources. We have also developed sophisticated radiative transfer (RT) models of these protostars (Zhang & Tan 2018, ApJ, 853, 18). Fitting these models to both the SED and imaging data enables the most detailed constraints on both the density and temperature structures around the protostar. Knowledge of these quantities is essential for determining the abundances of p-H_2D^+ and o-H_2D^+ and the implications for molecular cloud age from the derived OPR of H_2 (Brünken et al. 2014).

Ancillary science: Additional science will be derived from the ancillary line observations of HCO^+(4-3), HCN(4-3) and DCO^+(5-4), which are all expected to be relatively strong towards the SOMA protostars. The measured line strengths will help constrain abundances and excitation conditions of the species, which will be compared to astrochemical models of the sources. This astrochemical modelling work is in progress, funded by VR and ERC (Hsu et al. 2020, MNRAS, sub.). Furthermore the line profiles of these species will constrain the kinematics of the dense, warm gas near the protostar, which can also be compared to theoretical model predictions, based on the physical models of Zhang & Tan (2018).



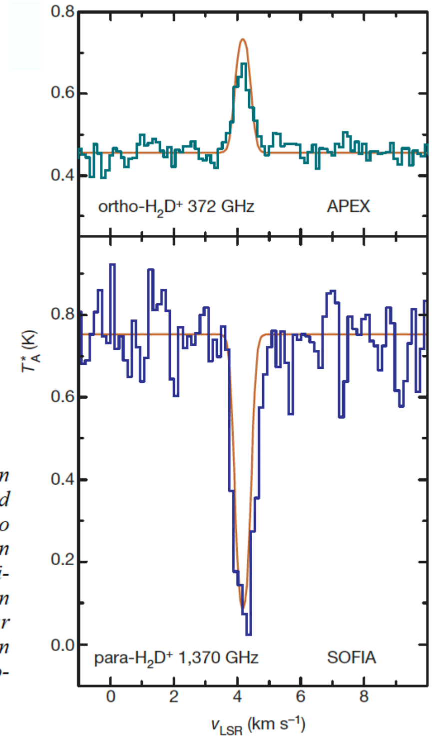


Figure 1: ***(a) Left:*** *Time evolution of OPR of H_2 and D_{frac} of N_2H^+ in the fiducial model of Kong et al. (2015) with T=15K and $n_H=10^5 cm^{-3}$ and cosmic ray ionization rate = $2.5\times10^{-17} s^{-1}$. Two dotted lines mark the times when these quantities approach within 10% of their final equilibrium values. This graph illustrates the anti-correlation between OPR of H_2 and D_{frac} of N_2H^+, which can then enable measurement of deuterated species to help trace molecular cloud ages.* ***(b) Right:*** *(From Brünken et al. 2014) The first detection of para-H_2D^+ at 1.37 THz with SOFIA (bottom panel) and the ortho-H_2D^+ line at 372 GHz detected with APEX (top panel).*

Summary: The ortho-to-para ratio of H_2 is the most basic astrochemical indicator of the age of molecular gas. However, the only practical way to measure this in star-forming regions is via the ortho- to-para ratio of H_2D^+. The only way to measure this requires the unique capabilities of SOFIA-GREAT for p-H_2D^+ (also Herschel was unable to carry out this observation) in combination with ground-based observations of o-H_2D^+. The technique has been demonstrated in a single nearby low-mass protostar by Brünken et al. (2014), with the result having a large impact. Our proposal involves extending this to a much larger sample. The SOFIA-GREAT observations have been proposed for in the most recent cycle (Sept. 2020; PI: J. Tan) for these relatively cool sources that still have bright 220 micron flux from the SOMA survey. Here we request o-H_2D^+ observations that are needed to complete the measurement of the OPR ratio to achieve the main science goal.

Technical Remarks

Instrument Setup: The o-H_2D^+ line at 372.421 GHz can be observed only in the USB of SEPIA345. We will centre the SEPIA345 USB on the o-H_2D^+ line frequency. We will also be able to observe HCO^+(4-3), HCN(4-3) and DCO^+(5-4).

Observing Time Estimate: We estimate the telescope time based on APEX observations of our primary line, o-H_2D^+ line at 372.421 GHz. The peak brightness of this line observed towards IRAS 16293-2422 A/B is TA* $\sim$ 0.7 K (Brünken et al. 2014). We request a 0.1 K rms in channels with a spectral resolution of 0.05 km/s, needed to detect expected line strengths with S/N $>$ 10 and resolve the line profile (even with a factor of 4 smoothing in velocity). Most sources except one have at least 60 deg elevation at APEX sites in July. Using the ON/OFF time estimator V7.3, it would require total 11.4 hour (including 10% additional overhead) for all 5 sources assuming 4 source elevations of 60 deg in PWV = 0.7mm weather and one source elevation of 50 deg in PWV = 0.7mm weather. The good weather is necessary because the o-H_2D^+ line is close to the edge of a strong atmospheric absorption feature.

Students involved

Student	Level	Applicant	Supervisor	Applicant	Expected completion date	Data required
Mr. Chi Yan Law	Doctor	Yes	Prof Jonathan Tan	Yes	2023/12	Yes
Chia-Jung Hsu	Doctor	Yes	Prof Jonathan Tan	Yes	2022/12	Yes

Linked proposal submitted to this TAC: No

Linked proposal submitted to other TACs: No

Relevant previous Allocations: Yes

107.F-9309(A),13.7 hrs, Not observed due to COVID-19 situation

No additional remarks

Observing run info :