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Dark cloud-type chemistry in PDRs with moderate UV field

Maria S. Kirsanova, Anna F. Punanova, Dmitry A. Semenov, Anton I. Vasyunin

We present a study of emission lines of small hydrocarbons C_2H and c-C_3H_2, and COMs precursors H_2CO and CH_3OH in order to better understand the possible chemical link between the molecular abundances and UV radiation field in photodissociation regions (PDRs). We study two PDRs around extended and compact HII regions with $G \leq 50$ Habings in the S235 star-forming complex. We find the highest abundances of both hydrocarbons on the edges of molecular clumps, while c-C_3H_2 is also abundant in the low-density expanding PDR around compact HII region S235 A. We see the highest methanol column density towards the positions with the UV field $G \approx 20-30$ Habings and explain them by reactive desorption from the dust grains. The N_{C_2H}/N_{CH_3OH} ratio is lower by a factor of few or the order of magnitude in comparison with the Horsehead and Orion Bar PDRs. The ratio is similar to the value observed in hot corinos in the Perseus cloud. We conclude that ion-molecular and grain surface chemical routes rule the molecular abundances in the PDRs, and the PDRs inherit molecular abundances from the previous dark stage of molecular cloud evolution in spite of massive stars already emitting in optics.

PDRでのchemistryに関する論文

・PDRでの炭素関連の輝線観測を行なった

・対象：S235←中程度のUV強度 (G~50)

・C2H、C3H2はクランプの縁で最大(C3H2はもう一箇所多いところもあった)

・メタノールはG~20-30のところで最大←ダストからの脱離

・組成の比率はPerseusのhot corinoぐらい（Orion馬頭星雲とは違う）

↑イオン分子反応とダスト表面反応が中心

・PDRのchemistryは以前の分子雲での状態を引き継ぐ

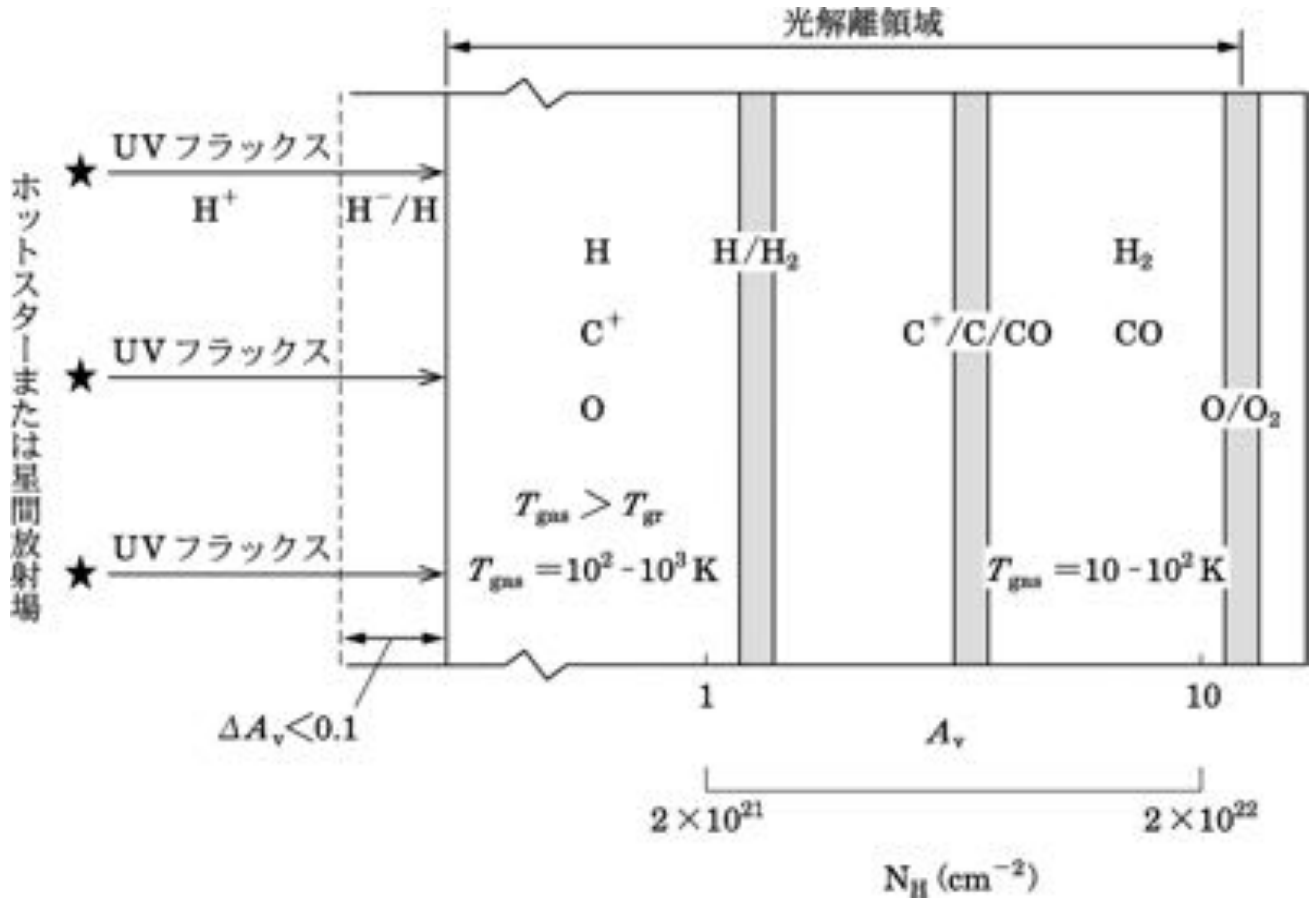
イントロ：UVとケミストリー

PDRでは豊富な化学進化が起きる

COMsの形成
　主に低温で進行すると考えられていたが、
　高温環境でも見つかっている

これまではOrion horsehead、Orion Bar PDRが
　　　　　　　　↑G=100　　　　　↑G=10^4~10^5
調べられて、UVの影響が議論されてきた。

UV強度が中程度の領域を調べる



PDRの概念図。天文学辞典より

観測対象：S235

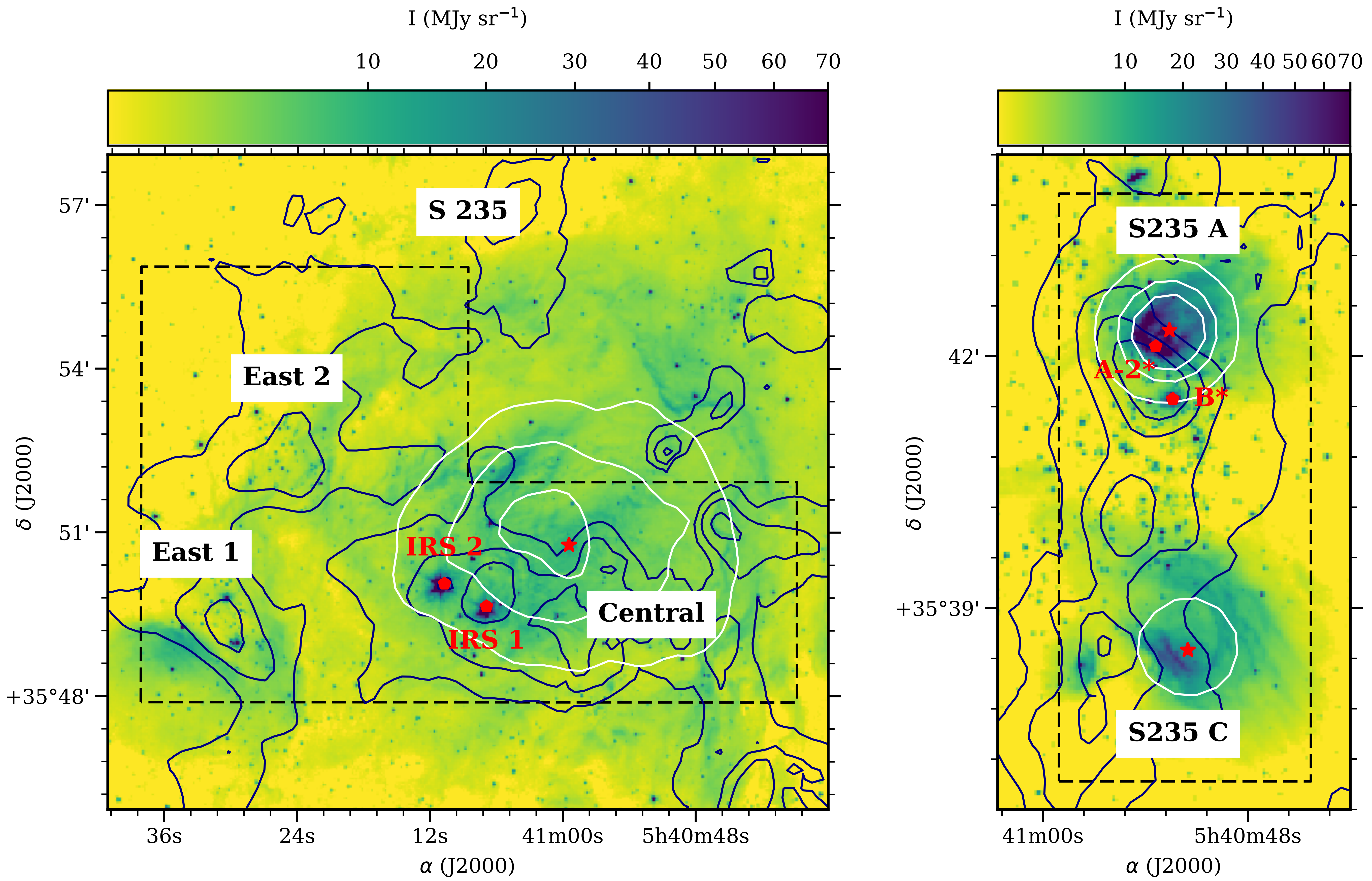


Figure 1. The 3.6 μm *Spitzer* image of the S235 (left) and S235 ABC (right) regions (Fazio & Megeath 2004). White contours show 1.4 GHz continuum emission from NVSS survey (Condon et al. 1998) at 0.01, 0.5 and 0.1 Jy/beam. Names of the H II regions as well as dense molecular clumps with the embedded young stellar clusters are given in bold face in white boxes. Black contours show levels of hydrogen column density: 1, 2, 3 and $4 \cdot 10^{22}$ cm^{-2} based on CO observations by Bieging et al. (2016). The ionizing sources of the H II regions are shown by the red stars. Red diamonds show other bright infrared sources: IRS 1, IRS 2 (Evans & Blair 1981), S235 B* (Boley et al. 2009) and S235 A-2* (Kirsanova et al. 2020a). Black dashed line show the area mapped by IRAM 30-m telescope.

IRAM 30mで以下の分子を観測

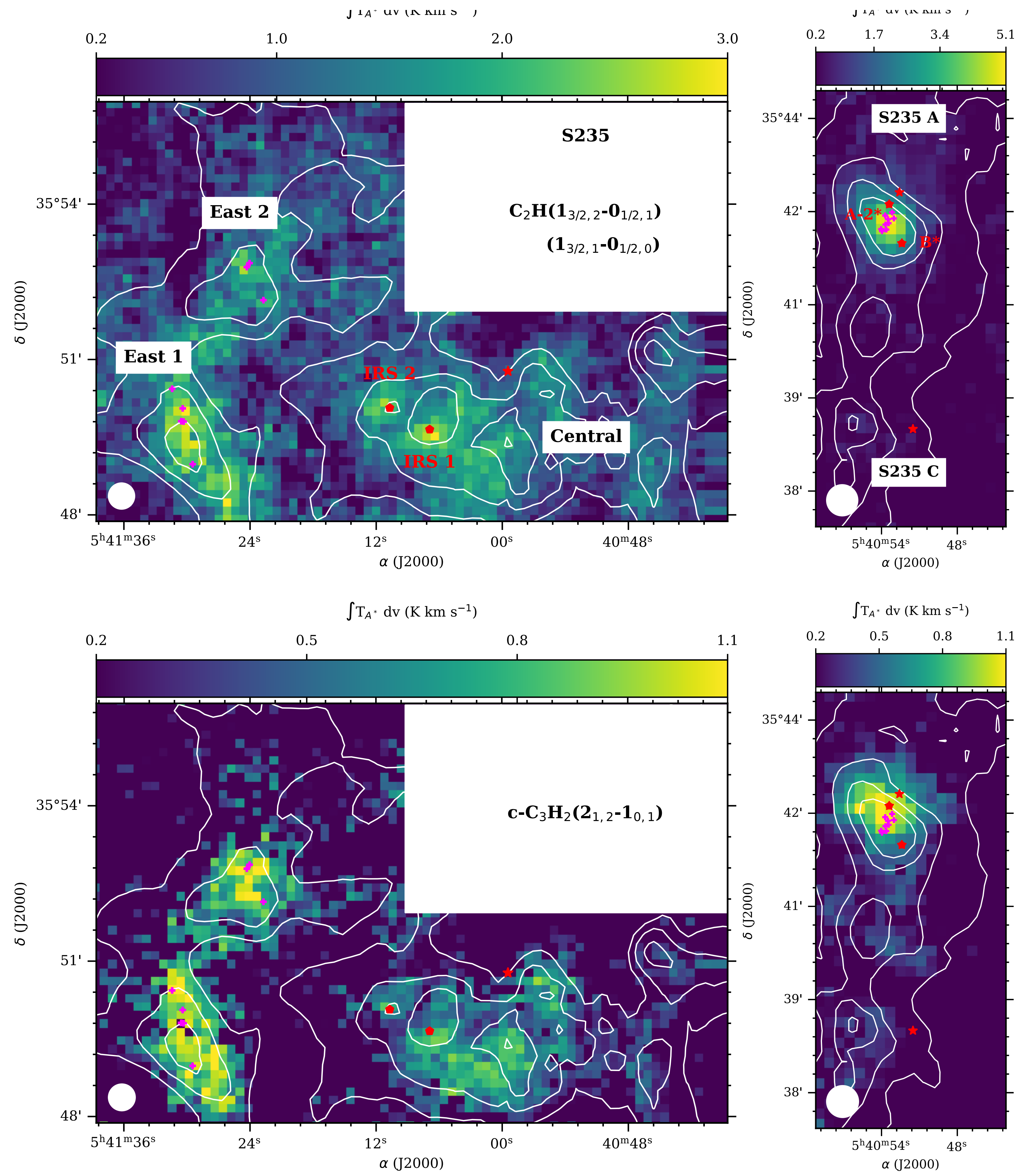
Molecule	Frequency (GHz)	$HPBW$ ($''$)	Δv_{res} (km s^{-1})	rms (K)	T_{sys} (K)
CH_3OH	84.5	29.3	0.18	0.04	105
$c\text{-}C_3H_2$	85.3	29.0	0.18	0.04	105
C_2H	87.3	28.3	0.17	0.05	96
HCN	88.6	27.9	0.17	0.04	96
H_2CO	140.8	17.6	0.11	0.13	156
CH_3OH	143.9	17.2	0.10	0.12	164
CH_3OH	145.1	17.0	0.10	0.12	164
$c\text{-}C_3H_2$	145.1	17.0	0.10	0.12	164

Table 1. Observation parameters.

左図：extended HII regionが1つ

右図：compact HII regionが2つ

結果：強度map

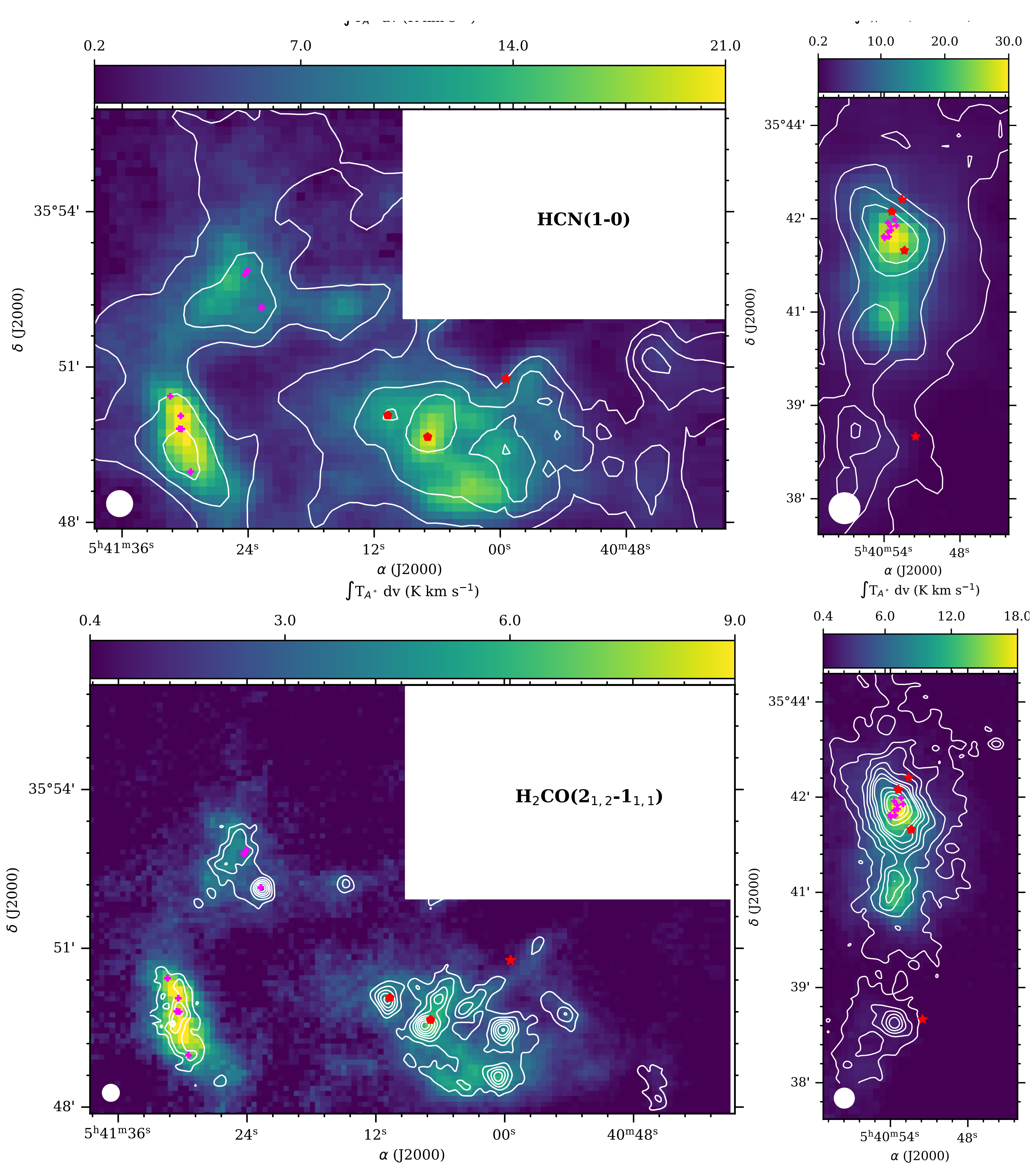


contourはCOに基づく面密度

COに近い分布

全体に広く分布

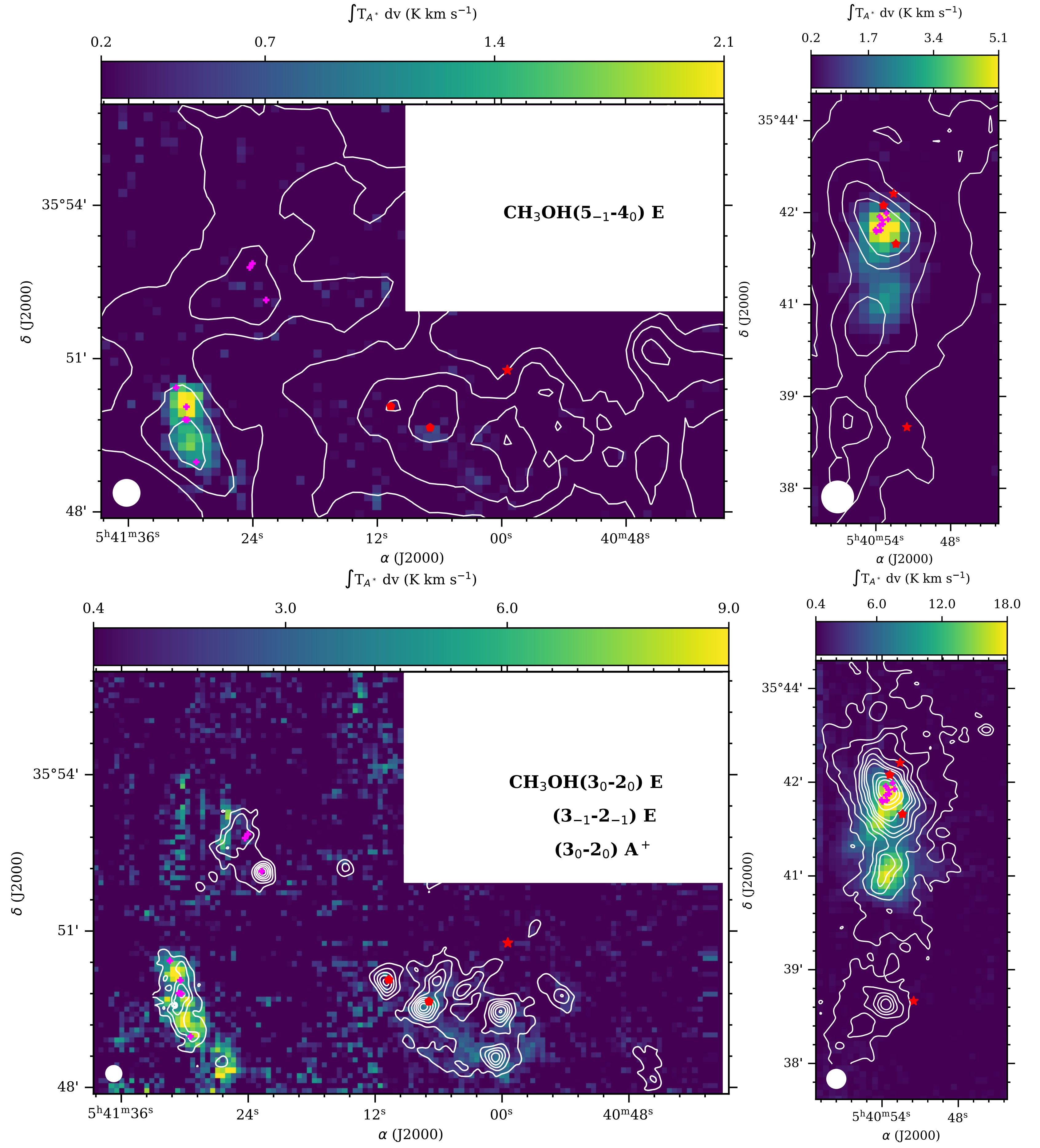
S235ではC3H2はクランプの西側が明るい



contourはダスト連続波

この二つの分布は似ている

クランプの反対側が明るい(特にEast 2)



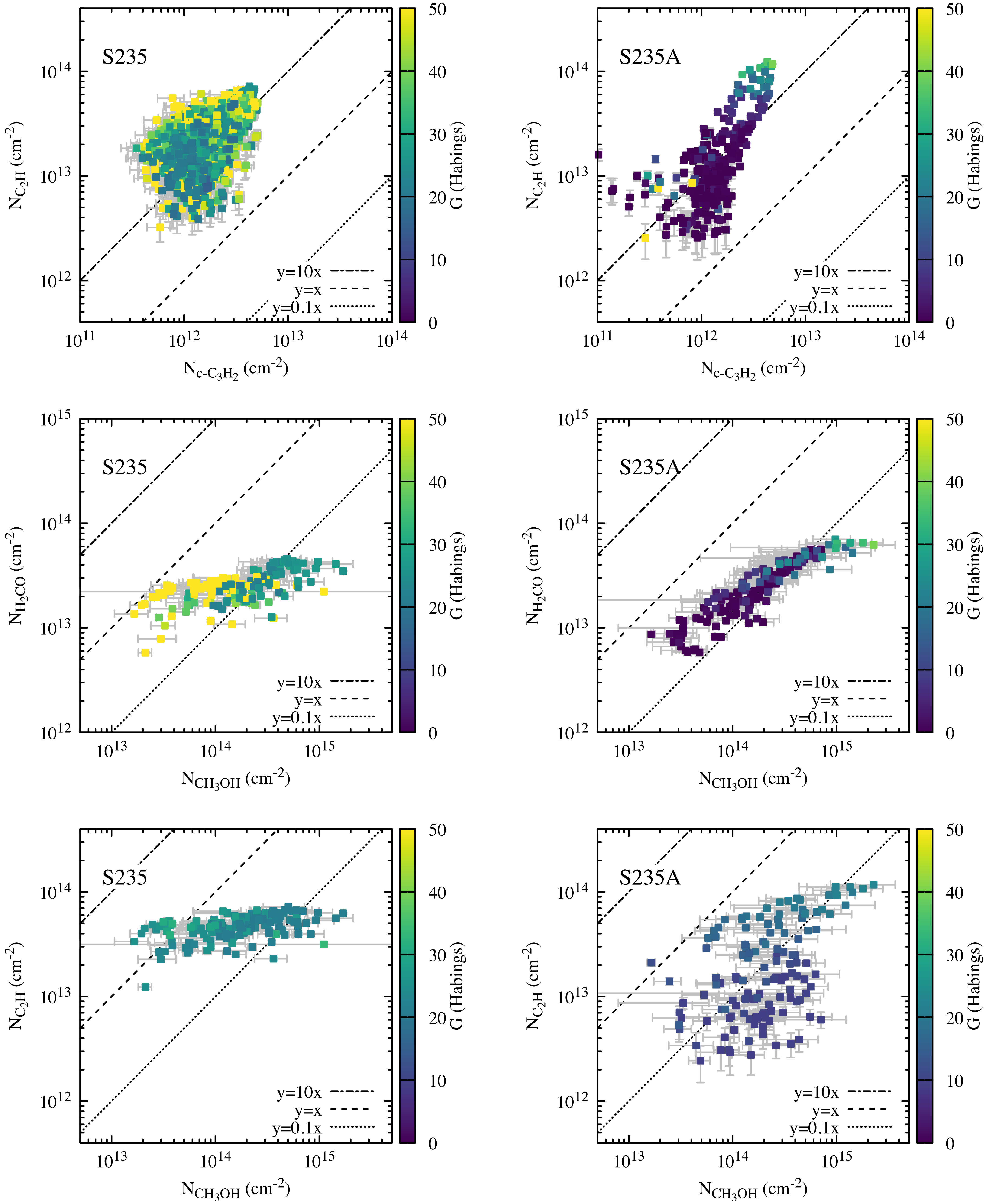
ダストのピークに集中

（スペクトルを見るとmaserになってるのも）

ダスト上でのreactive desorptionがメイン

過去の状態を引き継ぐ

結果：分子間、UV強度の関係



C3H2 / C2H について

G<30ではUVの増加に伴ってhydrocarbonは増加

G=40~50で最大になって大体一定

CH3OH / H2CO について

幅広い範囲(UV強度、CH3OH強度)で、H2COは同じような値

CH3OHはG=20~30で最大

全体的に H2CO < CH3OH なのはdark cloud chemistryと整合的

C2H / CH3OH について

C2HはS235ではほぼ一定だが、S235Aでは幅広く分布

↑強度の強いところしか受かってないから(?)

比はOrionの観測より遥かに(25倍)小さい

dark cloud chemistryでダスト表面でメタノール形成が起きてる

(>10^5 yr)

8 CRAFT (Cosmic Ray Acceleration From Turbulence) in Molecular Clouds

Brandt A. L. Gaches, Stefanie Walch, Alex Lazarian

Low-energy cosmic rays, in particular protons with energies below 1 GeV, are significant drivers of the thermochemistry of molecular clouds. However, these cosmic rays are also greatly impacted by energy losses and magnetic field transport effects in molecular gas. Explaining cosmic ray ionization rates of 10^{-16} s^{-1} or greater in dense gas requires either a high external cosmic ray flux, or local sources of MeV-GeV cosmic ray protons. We present a new local source of low-energy cosmic rays in molecular clouds: first order Fermi-acceleration of protons in regions undergoing turbulent reconnection in molecular clouds. We show from energetic-based arguments there is sufficient energy within the magneto-hydrodynamic turbulent cascade to produce ionization rates compatible with inferred ionization rates in molecular clouds. As turbulent reconnection is a volume-filling process, the proposed mechanism can produce a near-homogeneous distribution of low-energy cosmic rays within molecular clouds.

乱流が駆動するcosmic rayに関する論文

・1 GeV以下のcosmic rayは分子雲でのケミストリーにとって非常に重要

・分子雲では減衰するので、外から持ち込むのは難しい

・乱流駆動の1次フェルミ加速によるその場でのcosmic rayの生成を
エネルギーの観点から考察する

・均一なcosmic rayの生成源になりうる

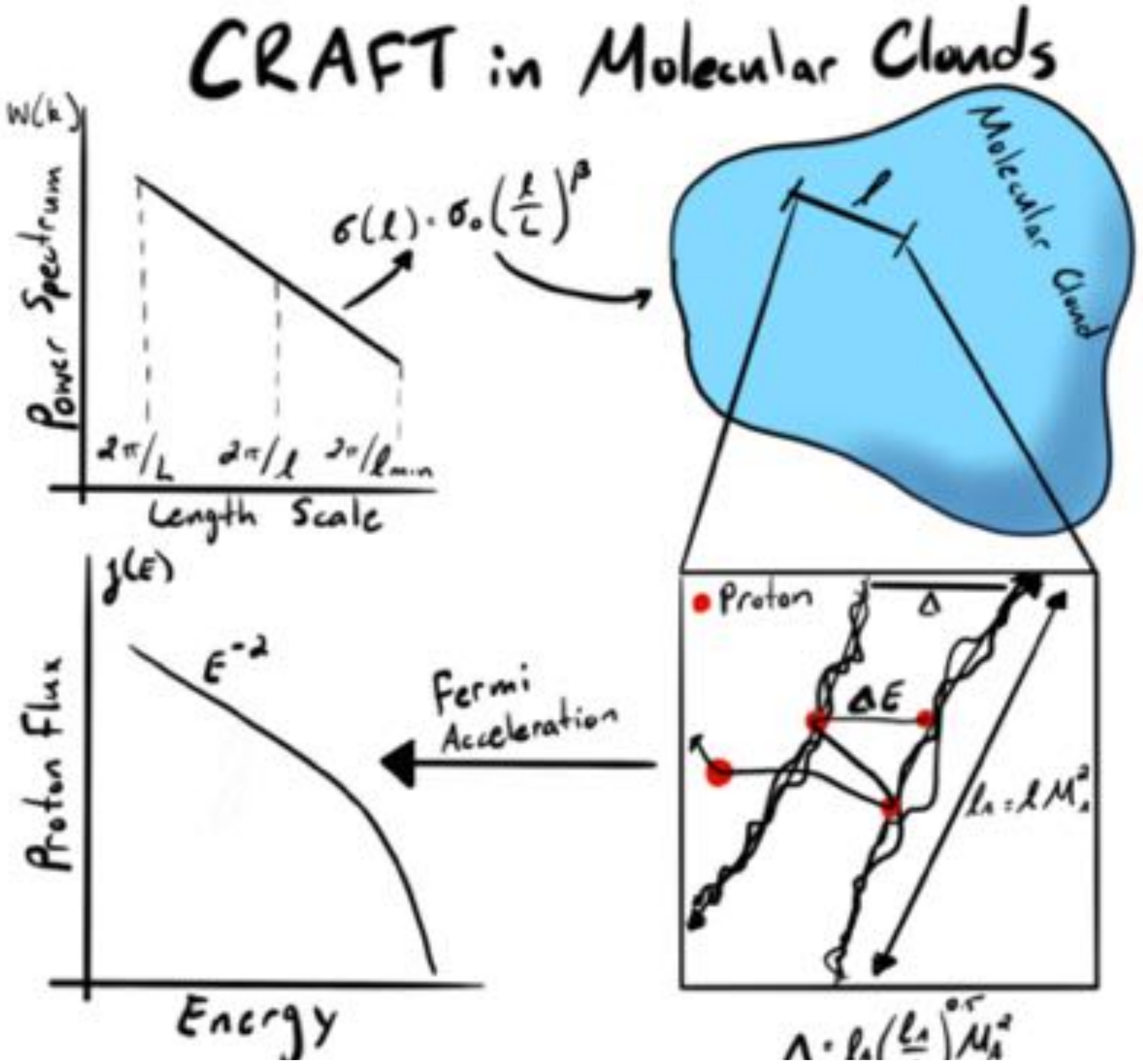
イントロ：cosmic rayの重要性、イオン化率

分子雲内での**化学反応はcosmic rayが出発点**

cosmic rayによる**イオン化率**は観測から
$10^{-17} < \zeta < 10^{-15}$ぐらいと見積もられている
（外部からcosmic rayがやってくるとすると）**分子雲の内側は遮蔽されてしまう**のでもっと低くなる
→その場でのcosmic rayの生成
これまでの案：protostellar jet, accretion shock, HII region, stellar windなど（どれも局所的）

本研究：乱流によるcosmic ray生成
・乱流のエネルギーが粒子加速に使われる
・一様なcosmic rayを生成
主に、**エネルギーの観点から**十分かどうかの議論を行う。

手法（仮定）



大事な式

$$\mathcal{N}_p(E) = \left|\frac{dE}{dt}\right|^{-1} \int_E^{E_{\max}} Q(E)dE \qquad (10)$$

消失　　注入

乱流強度を仮定して、その一部が粒子加速に使われると仮定
エネルギー損失と釣り合ってるとして、定常な値を得る

←層状の領域で粒子加速が起きるらしい

層状の領域で加速された粒子がcosmic rayとして広がる

フェルミ加速 （英語表記）Fermi acceleration

法則の辞典「フェルミ加速」の解説

フェルミ加速【Fermi acceleration】

宇宙線に含まれる高エネルギー粒子の加速機構としてフェルミが提案した機構で2種類ある．いずれの場合にも磁場を伴っている星間空間によって加速が行われる．

(1) 多数の磁気雲が高速で運動していて，荷電粒子はその間を弾性衝突しながら移動している．衝突のたびごとにエネルギーを得る．

コトバンクより

結果

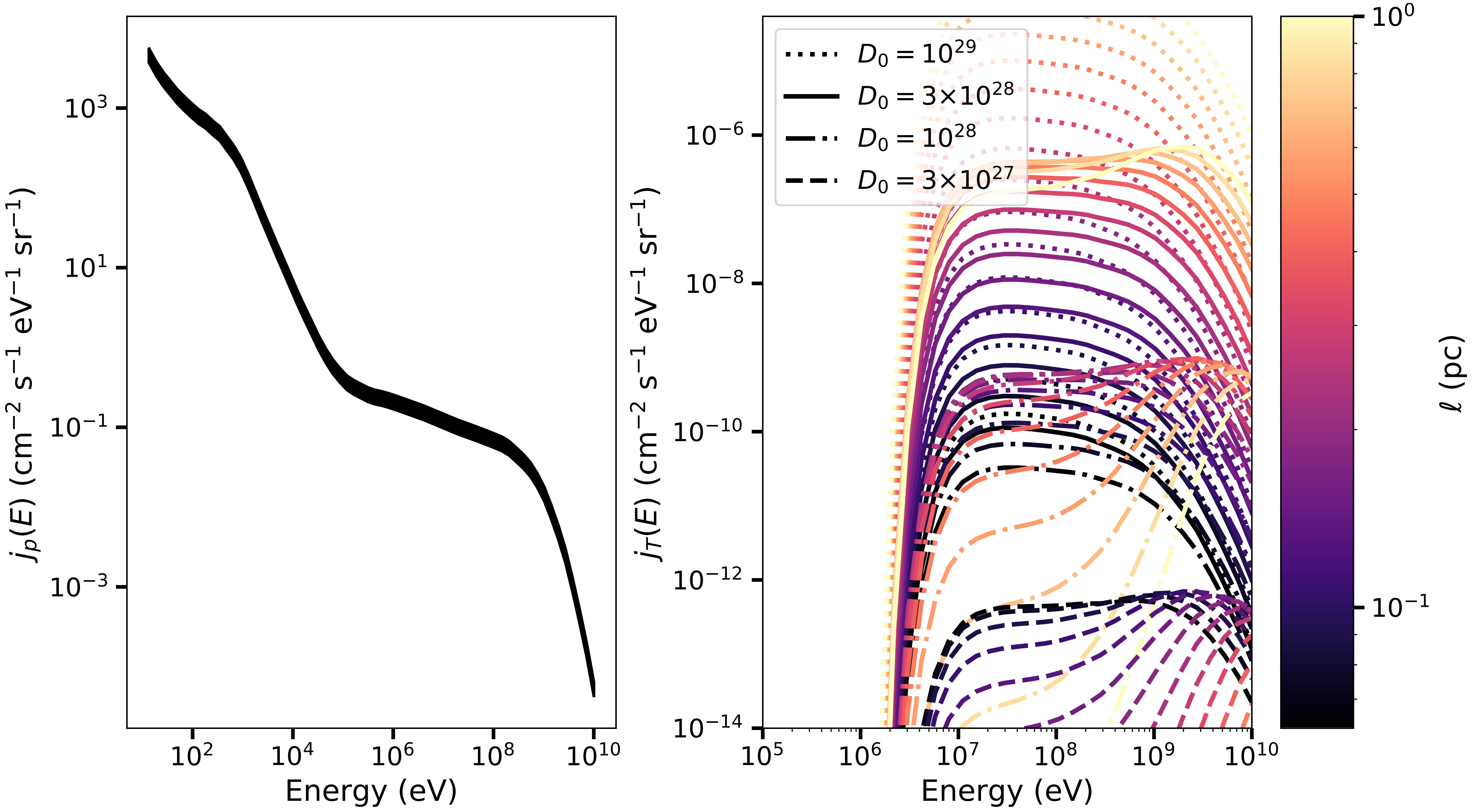
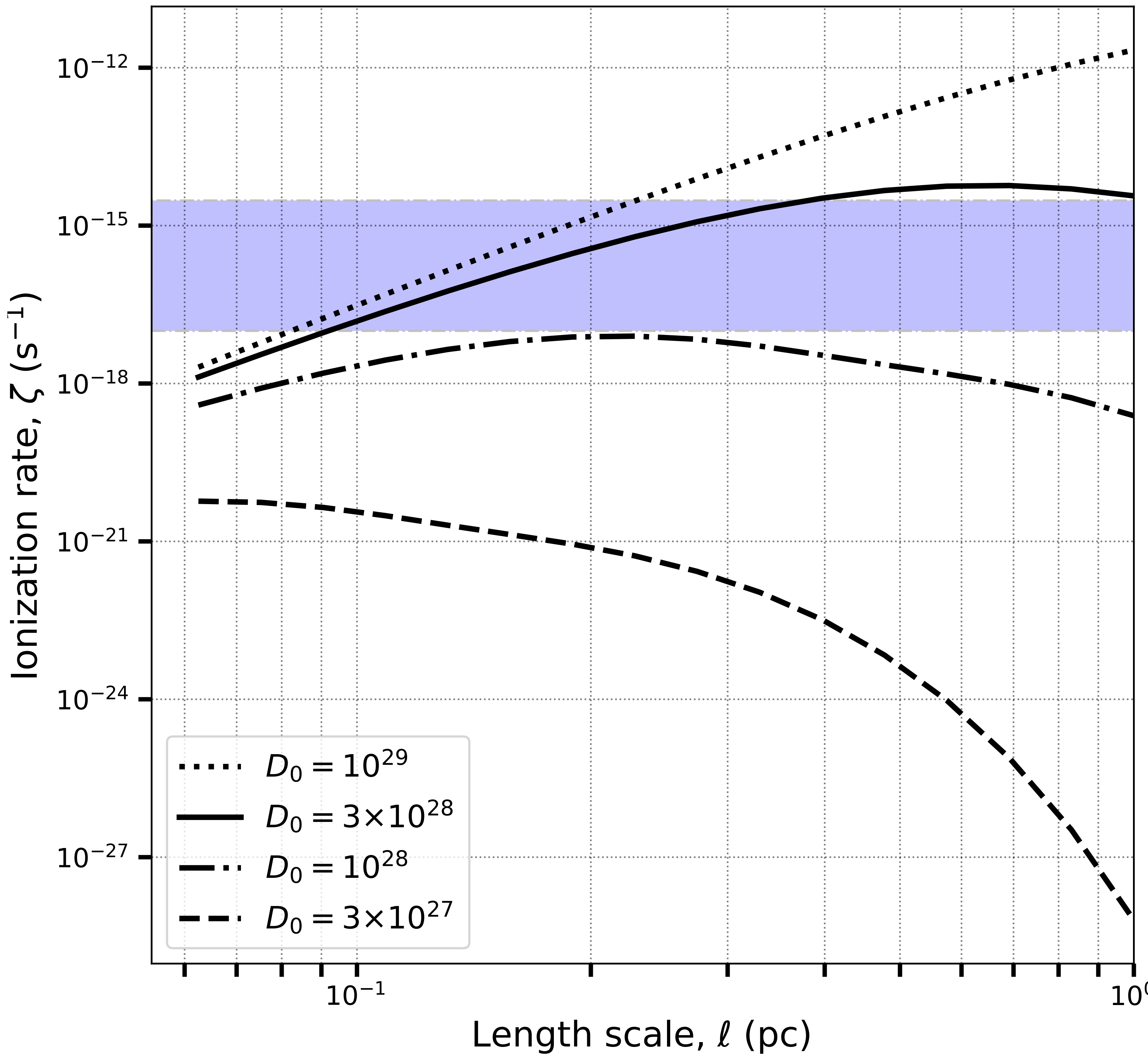


Figure 2. Left: Steady state solution for the flux, $j_p(E)$ as a function of energy for different values of ℓ. Right: Transported cosmic ray flux, $j_T(E)$, as a function of energy for different values of D_0 and ℓ. Note the different scales for the x- and y-axis of the subplots. Without including the impact of energy-losses and diffusion throughout the cloud, the resulting cosmic-ray flux would produce nonphysically high ionization rates.

・左図：cosmic rayの定常解
ζ~10^-9で大きすぎ
→ 分子雲全体で考える

・右：ある距離(l)でのcosmic rayの強度
拡散大でζ大
低エネルギーの粒子ほど減衰されやすい

結果



観測と合うのは、D=3x10^28ぐらいのとき

他の乱流モデルの場合

Table 1. Power-Spectrum Averaged Cloud Ionisation Rates

$D_0 =$	3×10^{27}	1×10^{28}	3×10^{28}	1×10^{29}
Fiducial	↓	9.1(−19)	7.5(−17)	2.5(−15)
Less Bound	↓	2.8(−18)	2.3(−16)	8.0(−15)
Strong Turb.	2.9(−18)	1.1(−15)	6.2(−14)	6.7(−13)
Kolmogorov Turb.	↓	1.1(−17)	1.7(−16)	1.6(−15)

Strong turbulenceではイオン化率が高い
銀河中心の観測となら合うかも(?)

・密度、磁場強度、イオン化率、乱流特性を観測から制限することでこの機構が正しいのかを判断することができるかも
・拡散係数の逆算にもなる

9 Touching the Stars: Using High-Resolution 3D Printing to Visualize Stellar Nurseries

Nia Imara, John C. Forbes, James C. Weaver

Owing to their intricate variable density architecture, and as a principal site of star formation, molecular clouds represent one of the most functionally significant, yet least understood features of our universe. To unravel the intrinsic structural complexity of molecular clouds, here we leverage the power of high-resolution bitmap-based 3D printing, which provides the opportunity to visualize astrophysical structures in a way that uniquely taps into the human brain's ability to recognize patterns suppressed in 2D representations. Using a new suite of nine simulations, each representing different physical extremes in the turbulent interstellar medium, as our source data, our workflow permits the unambiguous visualization of features in the 3D-printed models, such as quasi-planar structures, that are frequently obscured in traditional renderings and animations. Our bitmap-based 3D printing approach thus faithfully reproduces the subtle density gradient distribution within molecular clouds in a tangible, intuitive, and visually stunning manner. While laying the groundwork for the intuitive analysis of other structurally complex astronomical data sets, our 3D-printed models also serve as valuable tools in educational and public outreach endeavors.

3次元画像の可視化についての論文

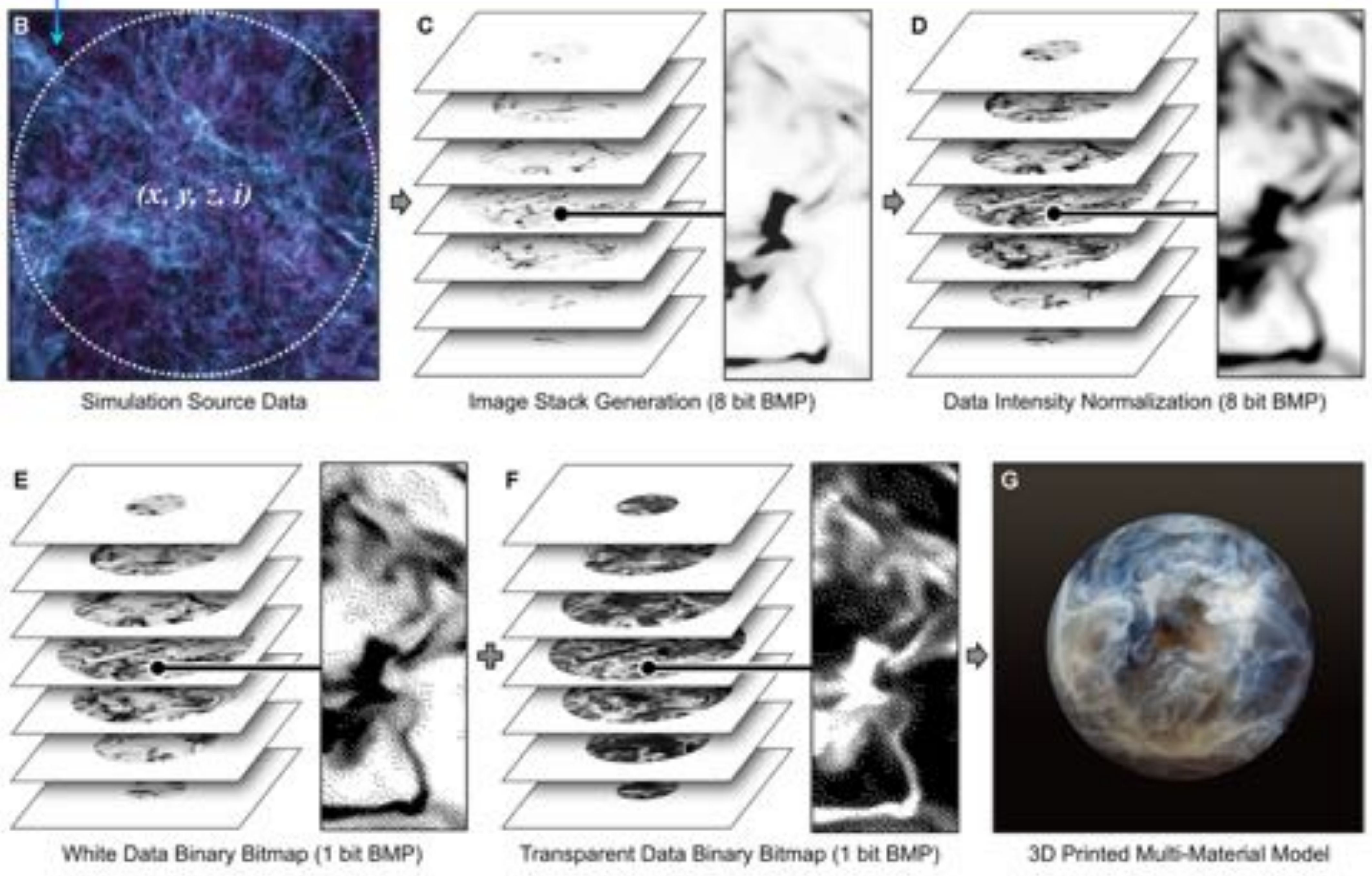
- 分子雲は非常に複雑な密度構造を持つ
- シミュレーション結果の可視化は難しい
- 3Dプリンターを使ってわかりやすく可視化
- これまでわかりにくかった平板上の構造とかもわかりやすく可視化

Floyd Steinberg dithering
でbinaryへ変換

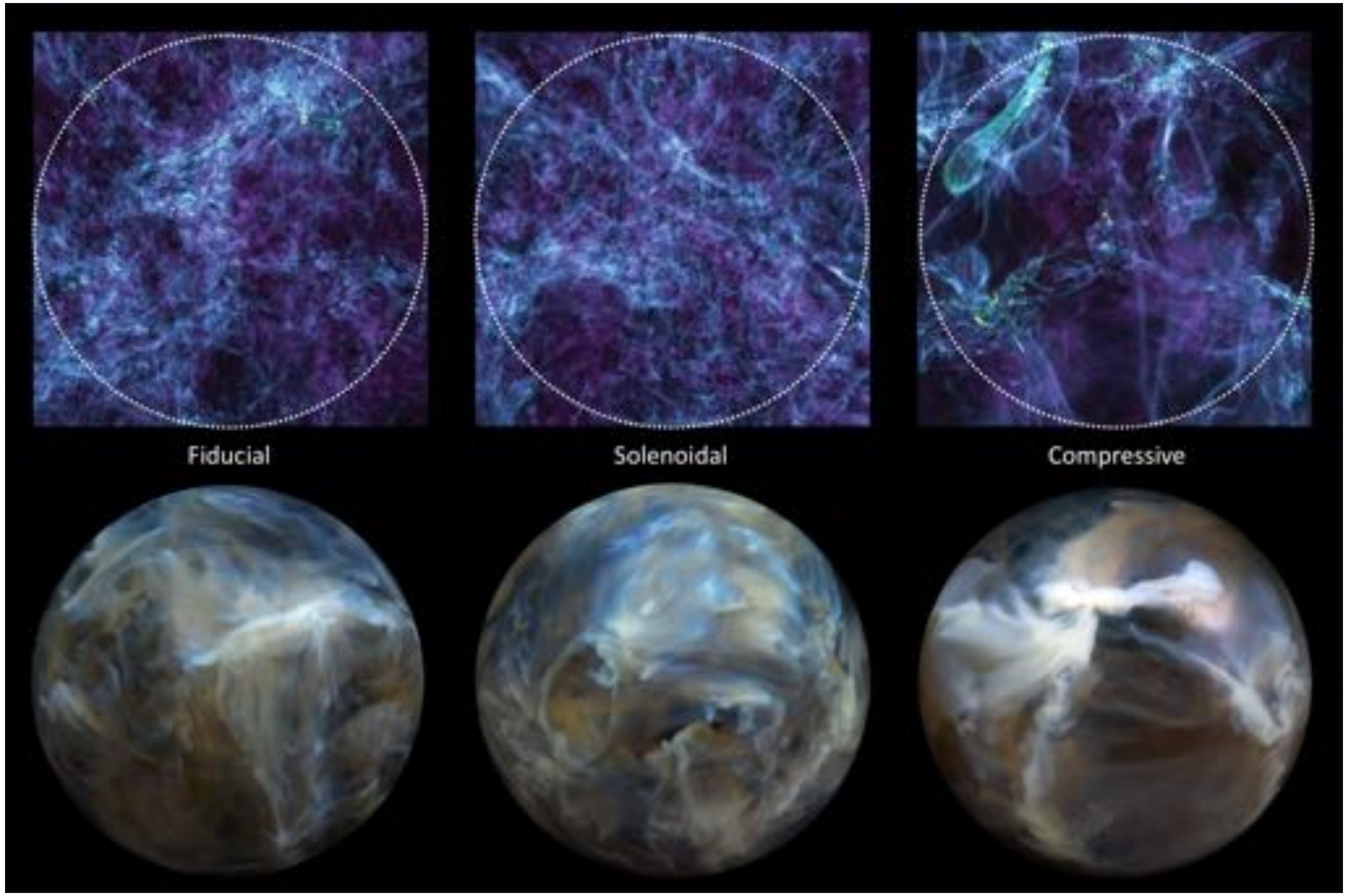
A

Molecular Cloud Simulation Parameters

Model	$\mathcal{M}$	$\mathcal{M}_A$	$\alpha_{\rm vir}$	Forcing	ρ_0 [g cm^{-3}]	L [pc]	σ_v [km s^{-1}]	β_0	B_0 [μG]
Fiducial	10	3	1.0	mixed	1.66×10^{-22}	25.1	2	0.6	1.7
Low Mach	5	3	1.0	mixed	1.66×10^{-22}	12.6	1	1.2	1.2
High Mach	20	3	1.0	mixed	1.66×10^{-22}	50.3	4	0.3	2.4
Low$\mathcal{M}_A$	10	1	1.0	mixed	1.66×10^{-22}	25.1	2	0.2	2.9
High$\mathcal{M}_A$	10	30	1.0	mixed	1.66×10^{-22}	25.1	2	6.0	0.5
Low Vir	10	3	0.5	mixed	1.66×10^{-22}	35.5	2	0.6	1.7
High Vir	10	3	2.0	mixed	1.66×10^{-22}	17.8	2	0.6	1.7
Sol	10	3	1.0	solenoidal	1.66×10^{-22}	25.1	2	0.6	1.7
Comp	10	3	1.0	compressive	1.66×10^{-22}	25.1	2	0.6	1.7



Imara, Forbes & Weaver



7 A survey for variable young stars with small telescopes: IV – Rotation Periods of YSOs in IC5070

Dirk Froebrich, Efthymia Derezea, Aleks Scholz, Jochen Eislöffel, Siegfried Vanaverbeke, Alfred Kume, Carys Herbert, Justyn Campbell-White, Niall Miller, Bringfried Stecklum, Sally V. Makin, Thomas Urtly, Francisco C. Soldán Alfaro, Erik Schwendeman, Geoffrey Stone, Mark Phillips, George Fleming, Rafael Gonzalez Farfán, Tonny Vanmunster, Michael A. Heald, Esteban Fernández Mañanes, Tim Nelson, Heinz-Bernd Eggenstein, Franky Dubois, Ludwig Logie, Steve Rau, Klaas Wiersema, Nick Quinn, Diego Rodriguez, Rafael Castillo García, Thomas Killestein, Tony Vale, Domenico Licchelli, Marc Deldem, Georg Piehler, Dawid Moździerski, Krzysztof Kotysz, Katarzyna Kowalska, Przemysław Mikołajczyk, Stephen R. L. Futcher, Timothy P. Long, Mario Morales Aimar, Barry Merrikin, Stephen Johnstone, Pavol A. Dubovský, Igor Kudzej, Roger Pickard, Samuel J. Billington, Lord Dover, Tarik Zegmott, Jack J. Evitts, Alejandra Traspas Munia, Mark C. Price

Studying rotational variability of young stars is enabling us to investigate a multitude of properties of young star-disk systems. We utilise high cadence, multi-wavelength optical time series data from the Hunting Outbursting Young Stars citizen science project to identify periodic variables in the Pelican Nebula (IC5070). A double blind study using nine different period-finding algorithms was conducted and a sample of 59 periodic variables was identified. We find that a combination of four period finding algorithms can achieve a completeness of 85% and a contamination of 30% in identifying periods in inhomogeneous data sets. The best performing methods are periodograms that rely on fitting a sine curve. Utilising GaiaEDR3 data, we have identified an unbiased sample of 40 periodic YSOs, without using any colour or magnitude selections. With a 98.9% probability we can exclude a homogeneous YSO period distribution. Instead we find a bi-modal distribution with peaks at three and eight days. The sample has a disk fraction of 50%, and its statistical properties are in agreement with other similarly aged YSOs populations. In particular, we confirm that the presence of the disk is linked to predominantly slow rotation and find a probability of 4.8×10^{-3} that the observed relation between period and presence of a disk has occurred by chance. In our sample of periodic variables, we also find pulsating giants, an eclipsing binary, and potential YSOs in the foreground of IC5070.

11

The first interferometric survey in the K-band of massive YSOs. On the hot dust, ionised gas, and binarity at au scales

E. Koumpia, W. -J. de Wit, R. D. Oudmaijer, A. J. Frost, S. Lumsden, A. Caratti o Garatti, S. P. Goodwin, B. Stecklum, I. Mendigutıa, J. D. Ilee, M. Vioque

Circumstellar discs are essential for high mass star formation, while multiplicity, in particular binarity, appears to be an inevitable outcome since the vast majority of massive stars (> 8 Msun) are found in binaries (up to 100%). We constrain the sizes of the dust and ionised gas (Brgamma) emission of the innermost regions towards a sample of six MYSOs, and provide high-mass binary statistics of young stars at 2-300 au scales using VLTI (GRAVITY, AMBER) observations. We determine the inner radius of the dust emission and place MYSOs with K-band measurements in a size-luminosity diagram for the first time, and compare our findings to T Tauris and Herbig AeBes. We also compare the observed K-band sizes to the sublimation radius predicted by three different disc scenarios. Lastly, we apply binary geometries to trace close binarity among MYSOs. The inner sizes of MYSOs, Herbig AeBe and T Tauri stars appear to follow a universal trend at which the sizes scale with the square-root of the stellar luminosity. The Brgamma emission originates from somewhat smaller and co-planar area compared to the 2.2 μm continuum emission. We discuss this new finding with respect to disc-wind or jet origin. Finally, we report an MYSO binary fraction of 17-25% at milli-arcsecond separations (2-300 au). The size-luminosity diagram indicates that the inner regions of discs around young stars scale with luminosity independently of the stellar mass. At the targeted scales (2-300 au), the MYSO binary fraction is lower than what was previously reported for the more evolved main sequence massive stars, which, if further confirmed, could implicate the predictions from massive binary formation theories. Lastly, we spatially resolve the crucial star/disc interface in a sample of MYSOs, showing that au-scale discs are prominent in high-mass star formation and similar to their low-mass equivalents.