Star Formation Newsletter

#348 30–36

崔仁士 (ASIAA)

No. 30

Evolution of dust in protoplanetary disks of eruptive stars

Eduard Vorobyov, Aleksandr M. Skliarevskii, Tamara Molyarova, Vitaly Akimkin, Yaroslav Pavlyuchenkov, Ágnes Kóspál, Hauyu Baobab Liu, Michihiro Takami, Anastasiia Topchieva

背景と概要

- 原始星のaccretionはepisodic
  - Accretion burstでluminosityが数桁上がる天体→FU Ori-type
  - Accretion burstによるluminosityの変化は円盤やエンベロープの環境を大きく変えるため重要
- 最近のサーベイによるとFU Ori-typeのような変光は従来考えられていたよりも一般的なよう
- しかしaccretion burstのタイムスケールの短さからburstによる変光を観測するのは難しい
  → Past luminosity burstを見つける方法が必要
- burstは円盤内のダストサイズ分布を変える→spectral indexの分布からpast burstを見つける方法をsimulationで模索

シミュレーションの設定

- Formation and Evolution of Stars and Disks (FEOSAD)というコード
- Flattened prestellar diskから始めてdiskの成長，進化を計算 (Molyarova+21)
- ガスとダストのダイナミクス，揮発性分子の進化を同時に解く
- 計算自体は二次元 (r,ϕ)だが，スケールハイトを計算することで鉛直方向の効果も取り入れている

For gas:

$$\frac{\partial \Sigma_{\rm g}}{\partial t} + \nabla_p \cdot (\Sigma_{\rm g} \boldsymbol{v}_p) = 0, \quad (1)$$

$$\frac{\partial}{\partial t}(\Sigma_{\rm g}\boldsymbol{v}_p) + [\nabla \cdot (\Sigma_{\rm g}\boldsymbol{v}_p \otimes \boldsymbol{v}_p)]_p = -\nabla_p \mathcal{P} + \Sigma_{\rm g}\boldsymbol{g}_p + (\nabla \cdot \boldsymbol{\Pi})_p - \Sigma_{\rm d,gr}\boldsymbol{f}_p, \quad (2)$$

$$\frac{\partial e}{\partial t} + \nabla_p \cdot (e\boldsymbol{v}_p) = -\mathcal{P}(\nabla_p \cdot \boldsymbol{v}_p) - \Lambda + \Gamma + (\nabla \boldsymbol{v})_{pp'} : \Pi_{pp'}, \quad (3)$$

- 流体力学，質量，モメンタム，エネルギー保存の式を解く
- 粘性トルク，粘性加熱，中心星からの輻射による加熱，ダストの熱放射によるcoolingが入ってる
- 粘性の効果はSakura–Sunyaev αで計算

(シミュレーションの設定続き)

For dust & volatiles:

- 1.0 μm以下のsmall dustとそれ以上のgrown dustの2成分

$$\frac{\partial \Sigma_{\rm d,sm}}{\partial t} + \nabla_p \cdot (\Sigma_{\rm d,sm} \boldsymbol{v}_p) = -S(a_{\rm max}), \qquad (4)$$

$$\frac{\partial \Sigma_{\rm d,gr}}{\partial t} + \nabla_p \cdot (\Sigma_{\rm d,gr} \boldsymbol{u}_p) = S(a_{\rm max}), \qquad (5)$$

$dN/da = a^{-3.5}$

$$\frac{\partial}{\partial t}(\Sigma_{\rm d,gr}\boldsymbol{u}_p) + [\nabla \cdot (\Sigma_{\rm d,gr}\boldsymbol{u}_p \otimes \boldsymbol{u}_p)]_p = \Sigma_{\rm d,gr}\,\boldsymbol{g}_p + \\ + \Sigma_{\rm d,gr}\boldsymbol{f}_p + S(a_{\rm max})\boldsymbol{v}_p, \qquad (6)$$

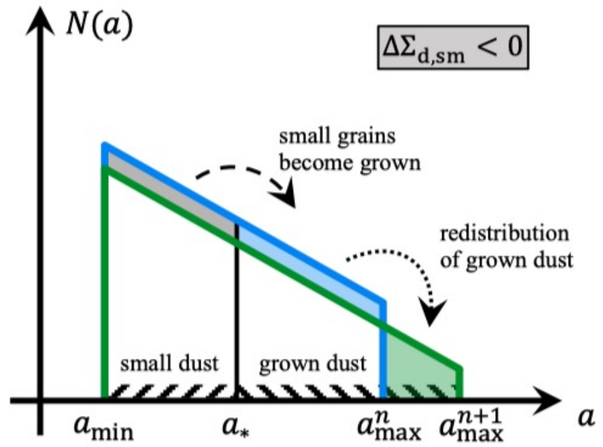
- small dustは式(4)，grown dustは式(5)，(6)に従う
  - small dustはgasにcouple，grown dustはdecouple
  - Sはsmall-to-grown dust conversion rate

- Grown dustの最大サイズはダスト成長の式と衝突破壊による成長限界で決定

$$\frac{\partial a_{\rm max}}{\partial t} + (\boldsymbol{u}_{\rm p} \cdot \nabla_p) a_{\rm max} = \mathcal{D}, \qquad a_{\rm frag} = \frac{2\Sigma_{\rm g} v_{\rm frag}^2}{3\pi \rho_{\rm s} \alpha c_{\rm s}^2},$$

$$v_{\rm frag} = \begin{cases} 15\,{\rm m\,s^{-1}}, & \text{if } \Sigma_{\rm ice}/\Sigma_{\rm d,gr} > K, \\ 1.5\,{\rm m\,s^{-1}}, & \text{if } \Sigma_{\rm ice}/\Sigma_{\rm d,gr} \leq K, \end{cases}$$

  - Kはiceの量によるダスト破壊の起こりやすさを決めるパラメータ
  - iceが少ないダストは破壊されやすい（合体しにくい）
  - CO, CO_2, H_2O, CH_4の固相，気相の変換を計算
  - （ケミストリーは入っていない）

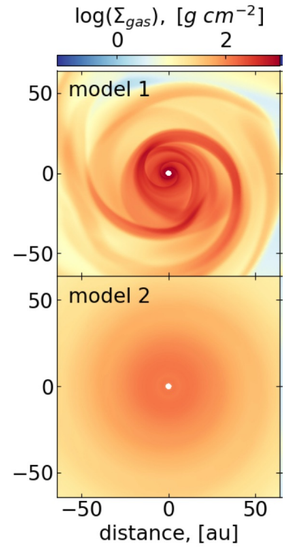


quantity	description	reference
ν	kinematic viscosity	$\nu = \alpha_{\rm visc} c_{\rm s} H_{\rm g}$
$H_{\rm g}$, $H_{\rm d}$	vertical scale heights of gas and dust	
$t_{\rm stop}$	stopping time	see eq. (8)
$\rho_{\rm s}$	material density of dust	$\rho_{\rm s} = 3$ g cm^{-3}
St	Stokes number	$\mathrm{St} = t_{\rm stop}\Omega$
$a_{\rm min}$	minimal size of small dust	$a_{\rm min} = 5 \cdot 10^{-7}$ cm
a_*	small and grown dust borderline	$a_* = 10^{-4}$ cm
$a_{\rm max}$	maximal size of grown dust	see eq. (9)
$\mathcal{D}$	collisional growth rate	see eq. (10)
$a_{\rm frag}$	fragmentational barrier	see eq. (12)
$v_{\rm frag}$	fragmentation velocity	see eq. (13)
p	slope of the grain size distribution	$p = 3.5$
$\alpha_{\rm visc}$	viscosity parameter	$\alpha_{\rm visc} = 10^{-2}$ and eq. (26)
$\zeta_{\rm d2g}$	dust-to-gas mass ratio	$\zeta_{\rm d2g} = \Sigma_{\rm d,tot}/\Sigma_{\rm g}$
κ_ν	opacity coefficient	cm^2 g^{-1}
$\alpha(\lambda_1, \lambda_2)$	spectral index	see eq. (24)

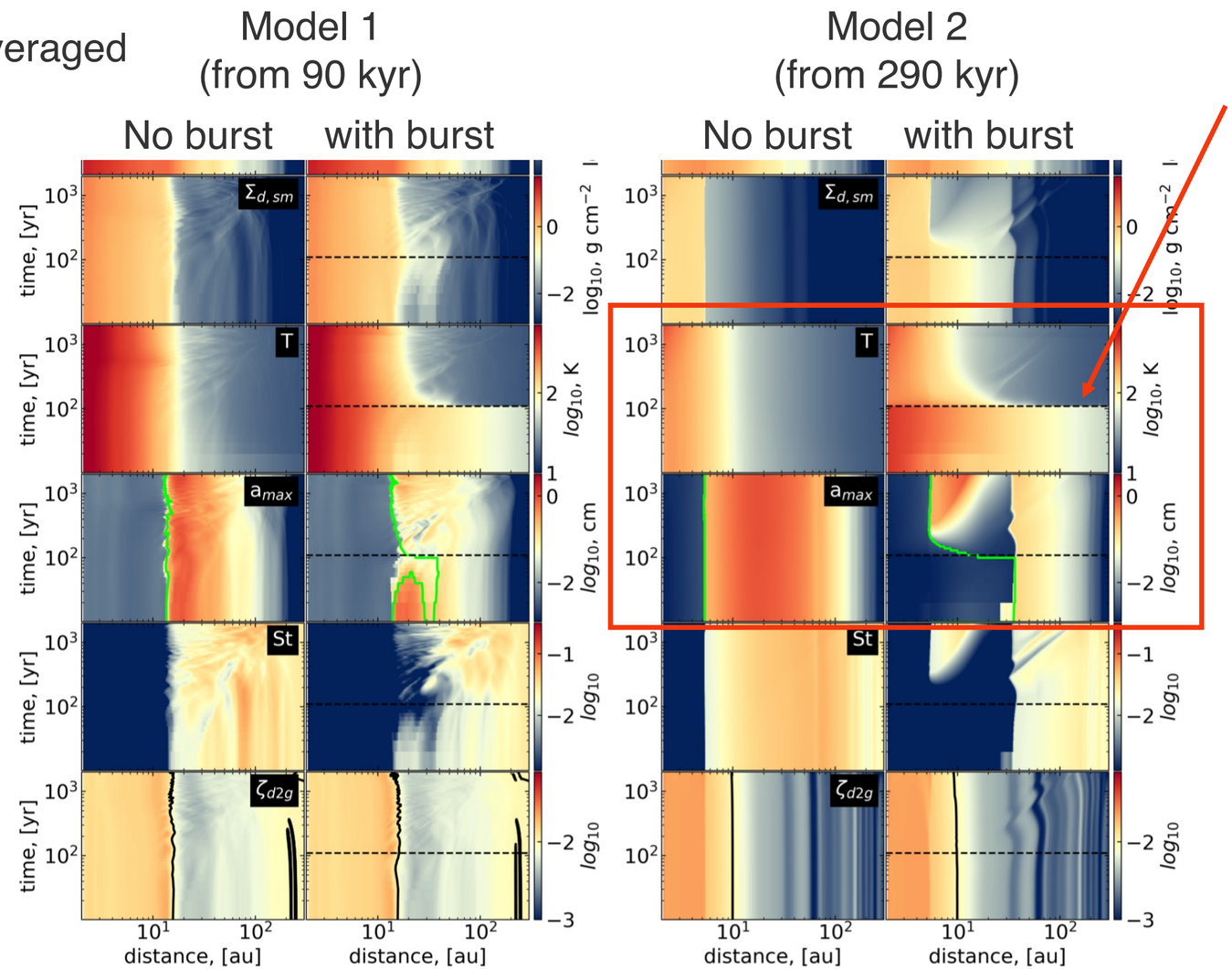
$M_{\rm core}$=0.66 $M_{\rm sun}$
M_*=0.46 $M_{\rm sun}$ at 500 kyr
(Molyarova+21)

モデル

- 90 kyr (model 1)と290 kyr (model 2)をそれぞれembedded phase, early T Tauri phaseと思って取り出す
- luminosityを300 L_{sun}にすることでaccretion burstを模擬，そこからの時間進化をさらに見る



Azimuthally averaged 1D profile



burst中 (100 yr)

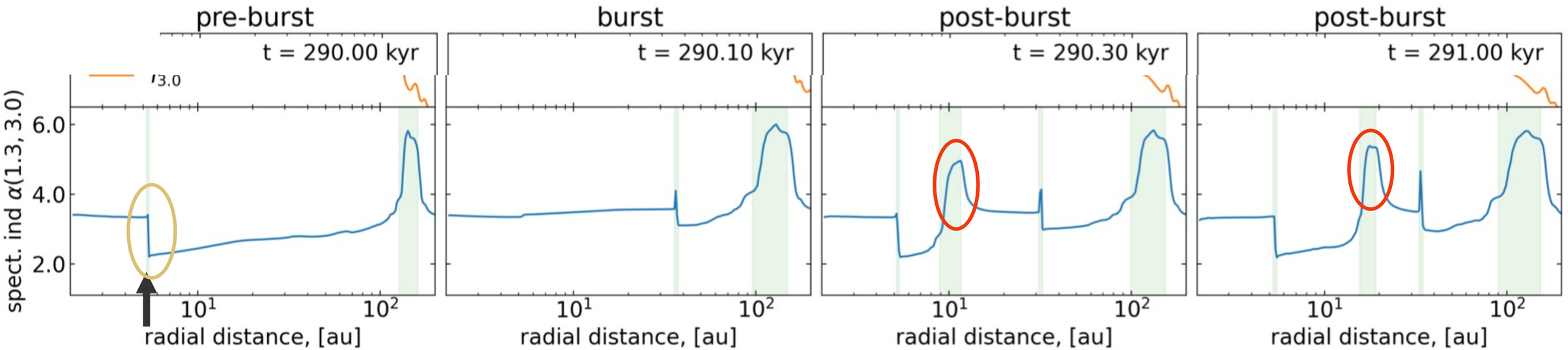
- 温度上昇，water snow lineは~5–14 auから~37–39 auまで広がる
- snow lineより内側では衝突破壊でdustの最大サイズは小さくなる

burst後 (100 yr–2 kyr)

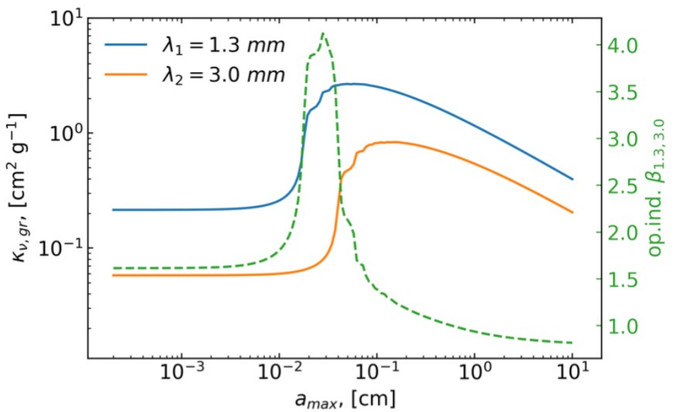
- 温度はすぐ下がりsnow lineも元へ戻る
- dustは最成長に~kyr単位の時間がかかる
- 円盤内側ほどダスト成長は早いのでa_{max}の分布に2箇所にシャープなカットオフができる

Spectral index (for model 2)

- small dust, grown dustの2成分でそれぞれopacityを計算，面密度と温度から1.3 mm, 3 mm (ALMA Band 6 & 3)間でのspectral index αの半径分布を計算



- Snow line前後でαのdrop
  - snow line内側では小さいダストが多くmm波ではoptically thin，外側ではgrown dustが多くoptically thick
- Post-burst期には広いαのピーク
  - burst後のダスト再成長の速度が内側ほど早いのでa_{max}の分布に谷ができるため
  - Cieza+16でpost-burst sourceと思われるV883 Oriに42 auに広いαのピーク，よく一致
- model 1ではspiralがあるため1次元の解析でこれらの特徴は見えない，バーストが弱いとダスト再成長のタイムスケールは早い



α~2+β

No. 32

A Census of Protostellar Outflows in Nearby Molecular Clouds

Duo Xu, Stella Offner, Robert Gutermuth, Shuo Kong, Hector G. Arce

背景と概要

- Outflowの分子雲へのフィードバックをよく知りたい
  - 近傍の分子雲で原始星からのoutflowが分子雲の乱流を維持する程度のエネルギーを放っていることが調べられてきている
- より正確にアウトフローのフィードバックを知るにはより正確なアウトフロー分布の調査が必要
- ディープラーニングを用いた手法CASI-3Dで近傍分子雲のアウトフローを調べ上げた

観測データ

- ^{12}CO, ^{13}CO J=1–0のサーベイ観測
- 文献からYSOカタログ

Telescope	Cloud	θ (")	rms (^{12}CO) (K)	rms (^{13}CO) (K)	Δv (km/s)
FARCO 13.7m	Ophiuchus	45/47	0.69	0.23	0.125
	Taurus		0.28	0.125	0.26/0.27
	Perseus		0.17	0.14	0.125
NRO 45m	Orion A	22	0.35	0.40	0.22

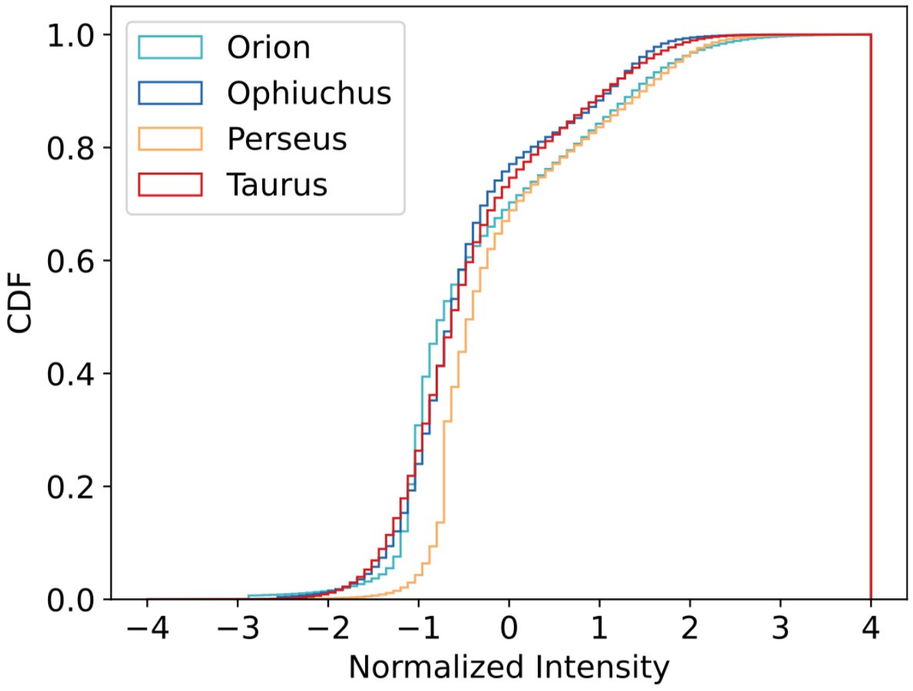
手法

CASI-3D

- Convolutional neural networks (CNNs)を用いたディープラーニングモデル
- MHDシミュレーションを元にモデルを作成 (詳細はXu+20)
- 2つのモデルME1とMF
  - それぞれ^{12}CO 2–1 emission, mass franction of stellar feedbackで学習

データプロセッシング

- emissionのログをとった後，平均値を引いてstdで割ることでデータを規格化
  - データのダイナミックレンジに対応するためらしい
- 全体のマップを64x64x32 (PPV)のchunksに分けてchunkごとにモデルをアプライ



Outflow mass

- ^{13}COが受かっていれば^{13}CO，そうでなければ^{12}COを使ってoptically thinを仮定して質量を導出
- ^{12}COのexcitation temperatureは25 Kかピーク強度どちらか高い方
- $[^{12}CO]/[^{13}CO]=62$, $[^{12}CO]/[H_2]=10^{-4}$

結果

- by eyeではどこがoutflowか区別は難しい
  - ほとんどcloud emissionが卓越しているため
- ME1モデルとMFモデルで違い
  - Ophiuchis L1688領域の例
    - ME1モデルの方がほとんどのemissionをoutflowと認識（総質量の81%）
    - MFモデルはL1688の総質量の12%だけをoutflowに付随と認識
- モデル予測からモーメントとエネルギーを計算
- False detectionの可能性については後に議論

$$P(VGsub) = \sum_{i,j,k} M_{\mathrm{CO},i,j,k}(v_{i,j,k} - \overline{v_{i,j}}), \quad (1)$$

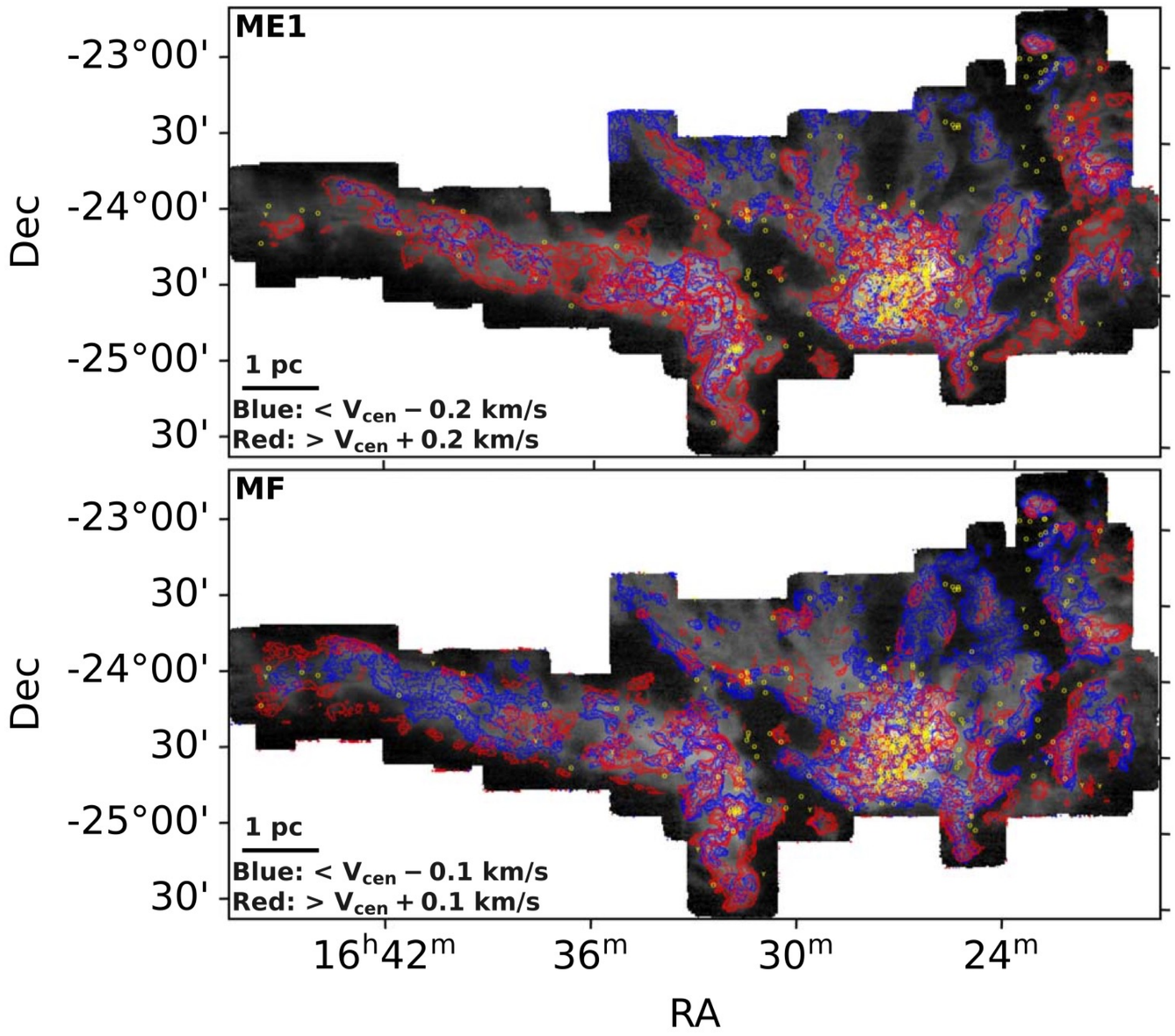
$$P(VGnonsub) = \sum_{i,j,k} M_{\mathrm{CO},i,j,k}(v_{i,j,k} - \overline{v_{\mathrm{global}}}). \quad (2)$$

$$E\left(VGsub\right) = \sum_{i,j,k} \frac{1}{2} M_{\mathrm{CO},i,j,k}(v_{i,j,k} - \overline{v_{i,j}}\Big)^2, \quad (3)$$

$$E\left(VGnonsub\right) = \sum_{i,j,k} \frac{1}{2} M_{\mathrm{CO},i,j,k}(v_{i,j,k} - \overline{v_{\mathrm{global}}}\Big)^2. \quad (4)$$

Background color: ^{12}CO map
Blue/red contour: 同定されたoutflow成分
Yellow points: YSOs

^{12}CO 1–0 of Ophiuchusの例

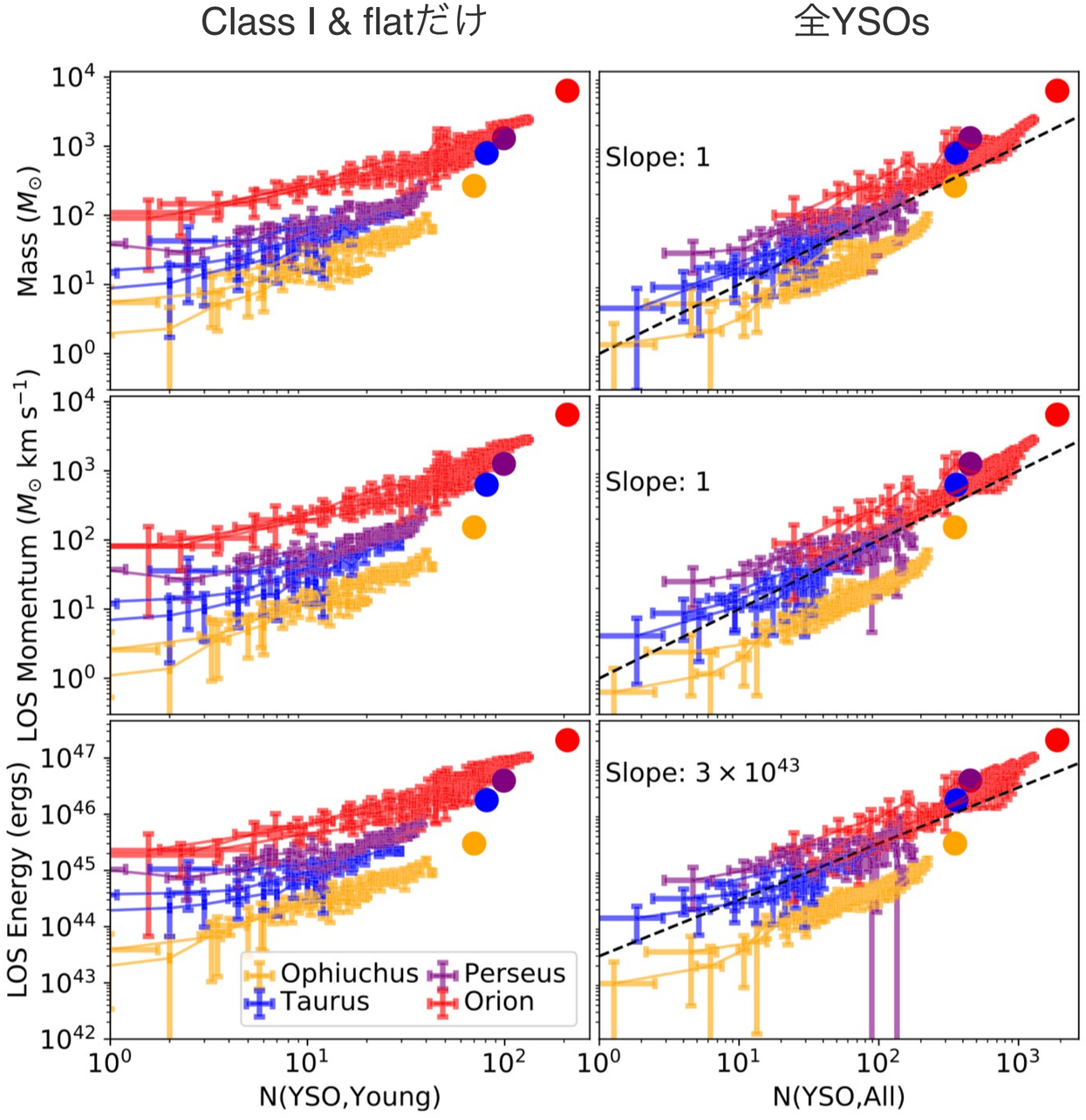


YSOとOutflowパラメータの相関

全体的に
- 各パラメータとYSO密度の間に正の相関
- 全部のYSOで見た方がcloudごとの違いは減る
  - Old YSO (Class II, III)もそれなりのoutflow massを持っていることを示唆
  - Outflowのdissipationのタイムスケールはdriving sourceの寿命より長いのでは

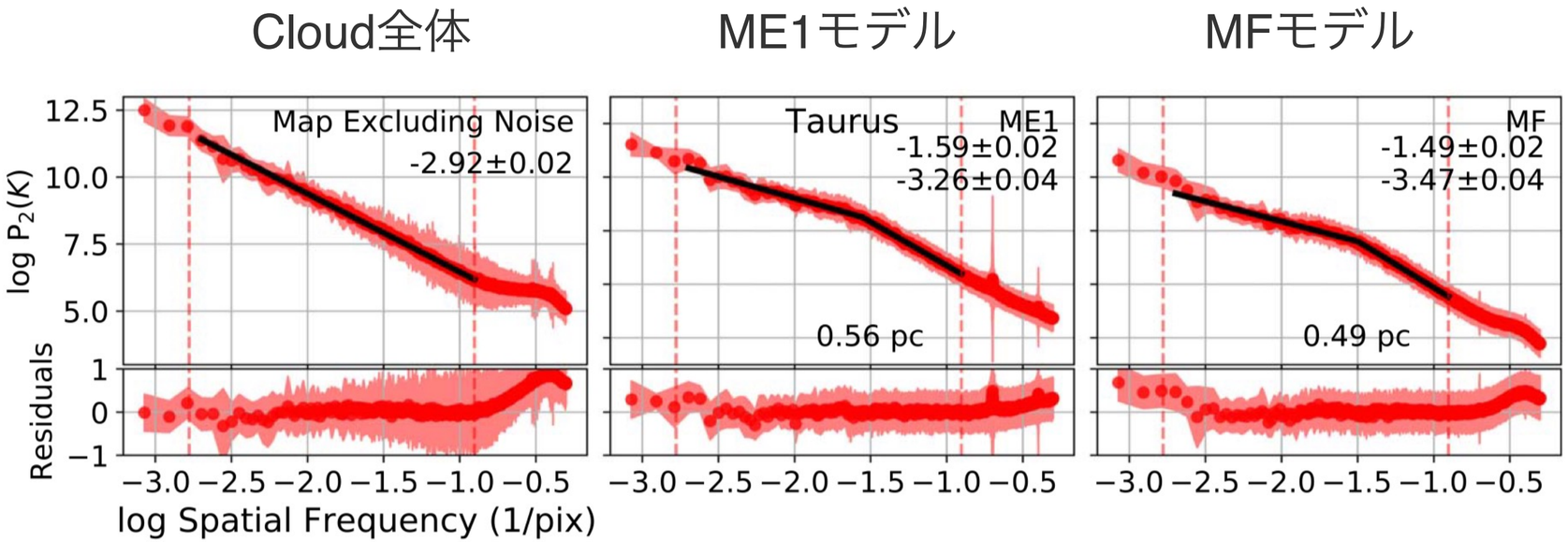
Mass
- Outflow massはcloud massの~10%
- Outflow mass per YSO ~1 M_{sun}
  - 中心星質量の10–30%が原始星から直接吹かれるoutflow massと考えられてるので，1 M_{sun}の星を考えるとほとんどは^{12}COで見てるのはentrainmentされたもの

Energy
- Cloud total energyの4–14 %
- 各cloudで先行研究で求められた値より5倍から一桁ほど大きな値 (~10^{46}–10^{47} ergs)
  - 従来方より低速度の成分まで検出対象になるため
- 先行研究のoutflowのkinetic energyがcloudの乱流を維持するのに十分な値というのを今回の手法でも確認



Spatial Power Spectrum (SPS)

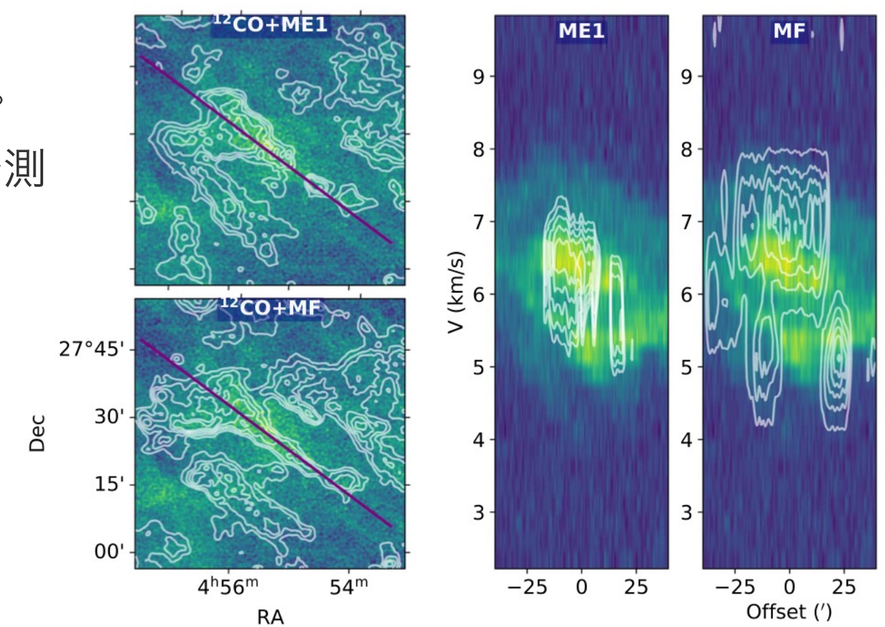
- ~0.5 pcにブレイク
  - Outflowによるエネルギー注入の典型的な空間スケール？



Outflow without driving source

- 右図のようにYSOがないところにもモデルではoutflowを検出
- コヒーレントな高速度の構造はoutflowと認識してしまう

カラー: 観測マップ
コントア: モデル予測



No. 35 **Kinematics of the molecular interstellar medium probed by Gaia: steep velocity dispersion-size relation, isotropic turbulence, and location-dependent energy dissipation**

Ji-Xuan Zhou, Guang-Xing Li, Bing-Qiu Chen

背景と概要

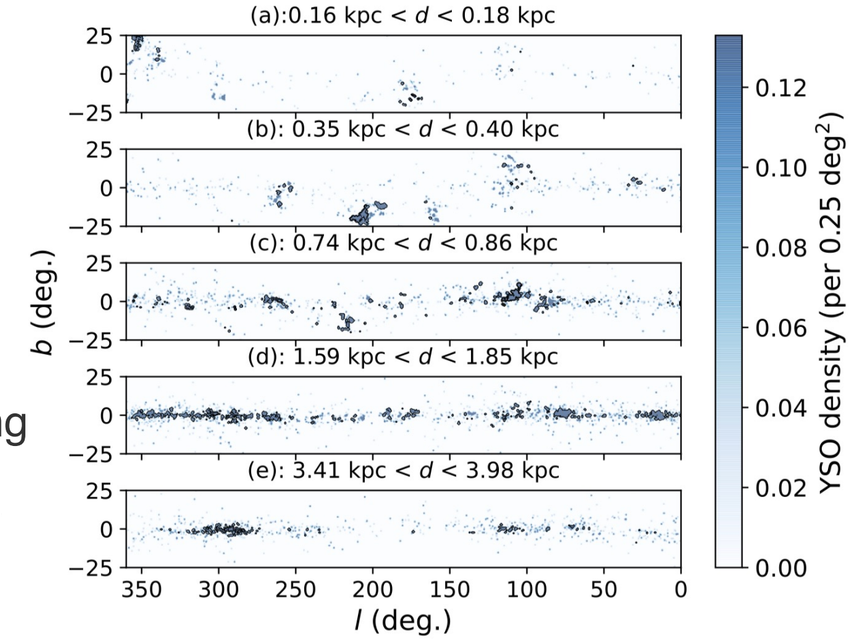
- 分子雲には乱流が普遍的に存在
- 銀河面に並行に銀河スケールに渡る分子雲の構造（e.g., extended Nessie）
  - 銀河スケールのshare motionが重要？その場合速度構造は銀河スケールでanisotropicになるはず
- Gaia DR2のデータを用いて銀河スケールの（YSOに付随する）ガスの力学を調べた
  - 銀経*l*, 銀緯*b*別々に（YSOに付随する）cloudガスの運動を調べた初めての例

観測データ

- 15149 Class I & Class II YSOs from Marton+16
- Gaia DR2からparallexesとproper motion
- <2 Myrの若いYSOsに絞る（付随する分子雲を見たいため）
- parallax errorが20%以上のものも除く

YSO associationsの決定

- YSOs density mapにDendrogramを適応
  - density mapは銀経*l*, 銀緯*b*, 距離log(*d*)でそれぞれ720, 100, 50 binsでbinningすることで作成
- 距離方向に大きな分散→ガウシアンフィットでprimaryな成分とその周辺だけを取る
- 最終的に150のYSO associationのサンプル

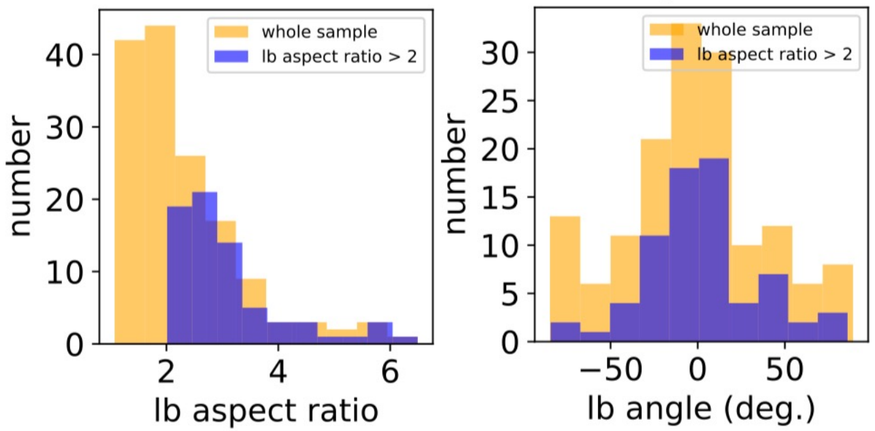


YSO associationのproperties

- 各YSOの(*l*, *b*, *d*)からassociationの平均距離，距離の分散，サイズ，速度分散を推定
- サイズ，速度は*l*, *b*方向それぞれ独立で計算
- Monte-Carloで各パラメータのエラーを推定

e.g. $r_l = 2.355\, d \cdot \mathrm{std}(l_i)$,

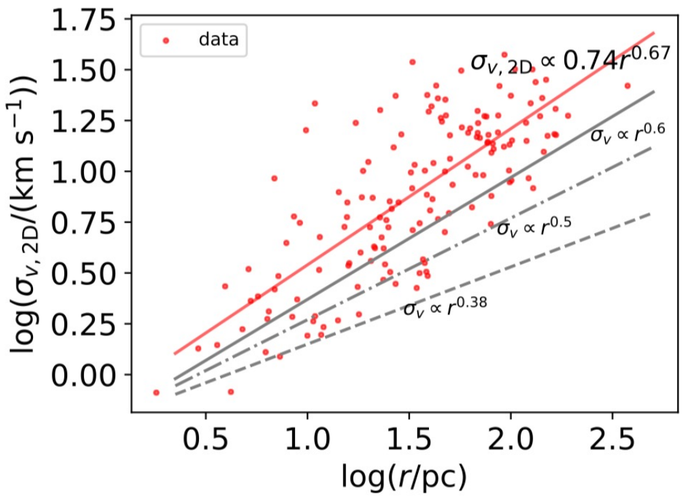
アスペクト比(*l*/*b*)



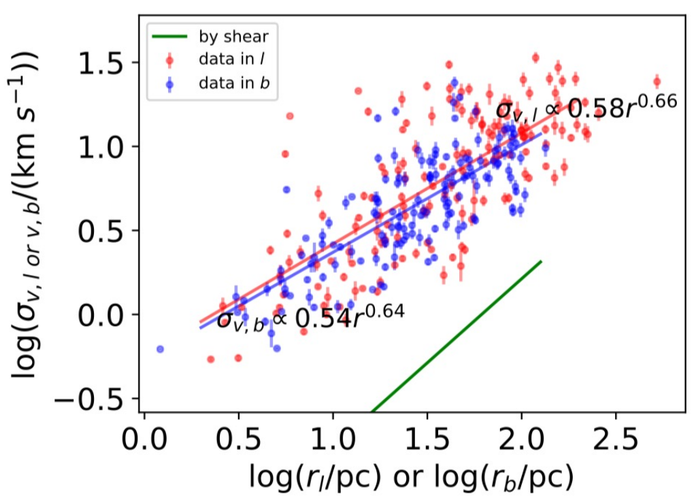
- 銀河面に整列している傾向
- 速度で見ても同じ傾向

速度分散のスケーリング側

(v_l,v_b)成分を合わせた場合



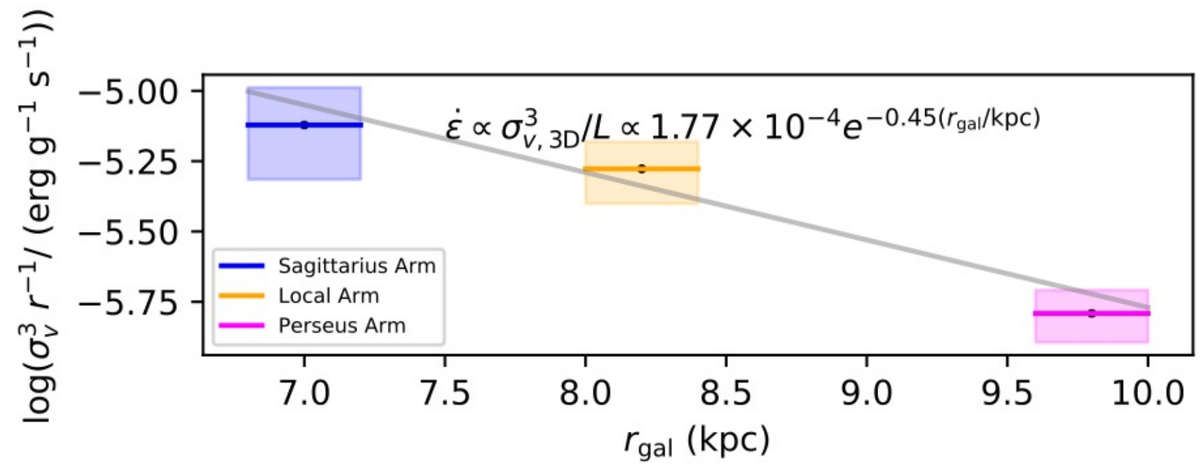
(v_l,v_b)成分別々



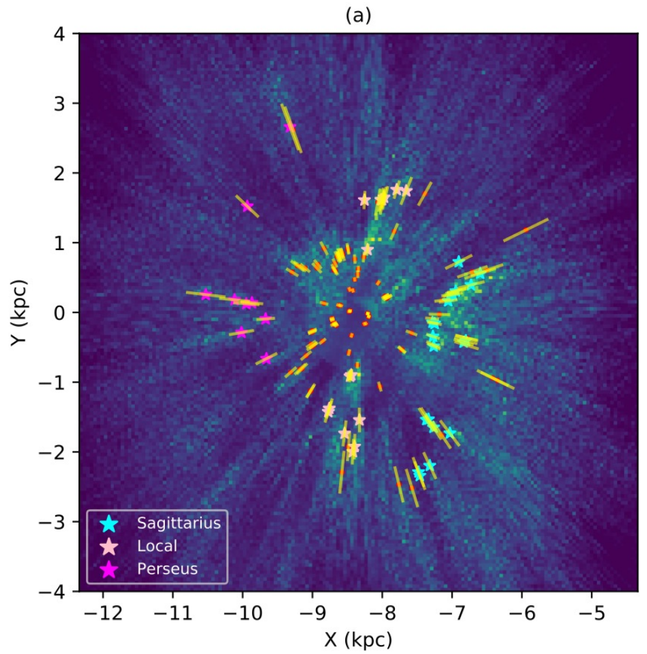
- (v_l,v_b)成分で速度分散は大体同じ
  - 密度は非等方でも速度分散は等方的
- 銀河のshare motion（緑線）はminor，速度分散は乱流由来そう
- スロープ~0.67はLarson's law（~0.38）より大きいが最近の研究結果と整合的
  - 圧縮性の乱流か重力収縮drivenの乱流で説明可能

Energy dissipation rate

- Energy dissipation rate: $\dot{\epsilon} = \sigma_v^3 / r$
  - r はassociationのサイズ（と思われる）で乱流がdrivenされるスケール
  - $\sigma_{v,\mathrm{3D}} = \sqrt{3/2}\sigma_{v,\mathrm{2D}}$



太陽系近傍を銀河の上方向から見た図



- 乱流は分子雲の衝突でdrivenされている説
  - Li17: 銀河のdiskと分子雲の共進化を調査

$$\sigma_{v,\mathrm{cloud}} \approx \sigma_{v,\mathrm{disc}} \left(\frac{\Sigma_{\mathrm{disc}}}{\Sigma_{\mathrm{cloud}}}\right)^{1/3} \left(\frac{r_{\mathrm{cloud}}}{H_{\mathrm{disc}}}\right)^{1/3}$$, where $\Sigma_{\mathrm{cloud}} \approx 10 M_\odot\ \mathrm{pc}^{-2}$ is mean surface density

  - Diskのスケールハイトと$\sigma_{v,\mathrm{disc}}$を無視すると$\dot{\epsilon} \propto \Sigma_{\mathrm{disc}}/\Sigma_{\mathrm{cloud}}$
  - Miville-Deschênes+17

$$\Sigma_{\mathrm{disk}} \propto e^{-0.5\, r_{\mathrm{gal}}}$$

  - 観測されたスロープ，–0.45とよく合う
  - Energy dissipation rateが銀河半径とともに下がるのは銀河面の密度減少（分子雲の衝突頻度の減少）が原因では

No. 31

Is the molecular KS relationship universal down to low metallicities?

David J. Whitworth, Rowan J. Smith, Robin Tress, Scott T. Kay, Simon C. O. Glover, Mattia C. Sormani, Ralf S. Klessen ★ In recent years it has been speculated that in extreme low metallicity galactic environments, stars form in regions that lack H2. In this paper we investigate how changing the metallicity and UV-field strength of a galaxy affects the star formation within, and the molecular gas Kennicutt-Schmidt relation. Using extremely high resolution arepo simulations of isolated dwarf galaxies, we independently vary the metallicity and UV-field to between 110% solar neighbourhood values. We include a non-equilibrium, time-dependant chemical network to model the molecular composition of the ISM, and include the effects of gas shielding from an ambient UV field. Crucially our simulations directly model the gravitational collapse of gas into star-forming clumps and cores and their subsequent accretion using sink particles. In this first publication we find that reducing the metallicity and UV-field by a factor of 10 has no effect on star formation, and minimal effect on the cold, dense star forming gas. The cold gas depletion times are almost an order of magnitude longer than the molecular gas depletion time due to the presence of star formation in HI dominated cold gas. We study the H2 Kennicutt-Schmidt relationship that arises naturally within the simulations and find a near linear power law index of N = 1.09 +/- 0.014 in our fiducial 10% solar metallicity model. As the metallicity and UV-field are reduced this becomes moderately steeper, with a slope of N = 1.24 +/- 0.022 for our 1% solar metallicity and 1% solar UV field model.

No. 33

A Comprehensive Study of the Young Cluster IRAS 05100+3723: Properties, Surrounding Interstellar Matter, and Associated Star Formation

R. K. Yadav, M. R. Samal, E. Semenko, A. Zavagno, S. Vaddi, P. Prajapati, D. K. Ojha, A. K. Pandey, M. Ridsdill-Smith, J. Jose, S. Patra, S. Dutta, P. Irawati, S. Sharma, D. K. Sahu, N. Panwar ★ We present a comprehensive multiwavelength investigation of a likely massive young cluster 'IRAS 05100+3723' and its environment with the aim to understand its formation history and feedback effects. We find that IRAS 05100+3723 is a distant (∼3.2 kpc), moderate mass (∼500 $M_\odot$), young (∼3 Myr) cluster with its most massive star being an O8.5V-type. From spectral modeling, we estimate the effective temperature and log g of the star as ∼33,000 K and ∼3.8, respectively. Our radio continuum observations reveal that the star has ionized its environment forming an HII region of size ∼2.7 pc, temperature ∼5,700 K, and electron density ∼165 cm^{-3}. However, our large-scale dust maps reveal that it has heated the dust up to several parsecs (∼10 pc) in the range 17−28 K and the morphology of warm dust emission resembles a bipolar HII region. From dust and ^{13}CO gas analyses, we find evidences that the formation of the HII region has occurred at the very end of a long filamentary cloud around 3 Myr ago, likely due to edge collapse of the filament. We show that the HII region is currently compressing a clump of mass ∼2700 $M_\odot$ at its western outskirts, at the junction of the HII region and filament. We observe several 70 μm point sources of intermediate-mass and class 0 nature within the clump. We attribute these sources as the second generation stars of the complex. We propose that the star formation in the clump is either induced or being facilitated by the compression of the expanding HII region onto the inflowing filamentary material.

No. 34

Atomic Shocks in the Outflow of L1551 IRS 5 Identified with SOFIA-upGREAT Observations of [OI]

Yao-Lun Yang, Neal J. Evans II, Agata Karska, Lars E. Kristensen, Rebeca Aladro, Jon P. Ramsey, Joel D. Green, Jeong-Eun Lee ★ We present velocity resolved SOFIA/upGREAT observations of [OI] and [CII] lines toward a Class I protostar, L1551 IRS 5, and its outflows. The SOFIA observations detect [OI] emission toward only the protostar and [CII] emission toward the protostar and the red-shifted outflow. The [OI] emission has a width of ∼100 km s^{-1} only in the blue-shifted velocity, suggesting an origin in shocked gas. The [CII] lines are narrow, consistent with an origin in a photodissociation region. Differential dust extinction from the envelope due to the inclination of the outflows is the most likely cause of the missing red-shifted [OI] emission. Fitting the [OI] line profile with two Gaussian components, we find one component at the source velocity with a width of ∼20 km s^{-1} and another extremely broad component at -30 km s^{-1} with a width of 87.5 km s^{-1}, the latter of which has not been seen in L1551 IRS 5. The kinematics of these two components resemble cavity shocks in molecular outflows and spot shocks in jets. Radiative transfer calculations of the [OI], high-J CO, and H_2O lines in the cavity shocks indicate that [OI] dominates the oxygen budget, making up more than 70oxygen abundance and suggesting [O]/[H] of $\sim 1.5\times10^{-4}$. Attributing the extremely broad [OI] component to atomic winds, we estimate the intrinsic mass loss rate of $(1.3\pm0.8)\times 10^{-6}$ $M_\odot$ yr^{-1}. The intrinsic mass loss rates derived from low-J CO, [OI], and HI are similar, supporting the model of momentum-conserving outflows, where the atomic wind carries most momentum and drives the molecular outflows.

No. 36

Magnetic field structure of OMC-3 in the far infrared revealed by SOFIA/HAWC+

Niko Zielinski, Sebastian Wolf ★ We report the SOFIA/HAWC+ band D (154 μm) and E (214 μm) polarimetric observations of the filamentary structure OMC-3 that is part of the Orion molecular cloud. The polarization pattern is uniform for both bands and parallel to the filament structure. The polarization degree decreases toward regions with high intensity for both bands, revealing a so called "polarization hole." We identified an optical depth effect in which polarized emission and extinction act as counteracting mechanisms as a potential contributor to this phenomenon. Assuming that the detected polarization is caused by the emission of magnetically aligned non-spherical dust grains, the inferred magnetic field is uniform and oriented perpendicular to the filament. The magnetic field strength derived from the polarization patterns at 154 μm and 214 μm amounts to 202 μG and 261 μG, respectively. The derived magnetic field direction is consistent with that derived from previous polarimetric observations in the far infrared and submillimeter (submm) wavelength range. Investigating the far-infrared polarization spectrum derived from the SOFIA/HAWC+ observations, we do not find a clear correlation between the polarization spectrum and cloud properties, namely, the column density, $N(H_2)$, and temperature, T.