Star Formation Newsletter #344 12-17

武藤恭之

No. 12

The IGRINS YSO Survey I. Stellar parameters of pre-main sequence stars in Taurus-Auriga

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We present fundamental parameters for 110 canonical K- & M-type ($1.3-0.13 M_{\odot}$) Taurus-Auriga young stellar objects (YSOs). The analysis produces a simultaneous determination of effective temperature ($T_{\rm eff}$), surface gravity (log g), magnetic field strength (B), and projected rotational velocity ($v \sin i$). Our method employed synthetic spectra and high-resolution (R$\sim$45,000) near-infrared spectra taken with the Immersion GRating INfrared Spectrometer (IGRINS) to fit specific K-band spectral regions most sensitive to those parameters. The use of these high-resolution spectra reduces the influence of distance uncertainties, reddening, and non-photospheric continuum emission on the parameter determinations. The median total (fit + systematic) uncertainties were 170 K, 0.28 dex, 0.60 kG, 2.5 km s^{-1} for $T_{\rm eff}$, log g, B, and $v \sin i$, respectively. We determined B for 41 Taurus YSOs (upper limits for the remainder) and find systematic offsets (lower $T_{\rm eff}$, higher log g and $v \sin i$) in parameters when B is measurable but not considered in the fit. The average log g for the Class II and Class III objects differs by 0.23$\pm$0.05dex, which is consistent with Class III objects being the more evolved members of the star-forming region. However, the dispersion in log g is greater than the uncertainties, which highlights how the YSO classification correlates with age (log g), yet there are exceptionally young (lower log g) Class III YSOs and relatively old (higher log g) Class II YSOs with unexplained evolutionary histories. The spectra from this work are provided in an online repository along with TW Hydrae Association (TWA) comparison objects and the model grid used in our analysis.

- Taurus-Auriga 領域の K/M型 YSO 110個について、赤外線の高分散分光をもとに、星のパラメータを推定
  - 有効温度、表面重力、磁場、回転
- Class II と Class III で、log g が 0.23dex 程度異なる
  - Class III の方が進化が進んでいるという描像と整合的
  - ただし、log g の分散は不定性より大きく、YSO 進化の多様性はありそう

No. 13

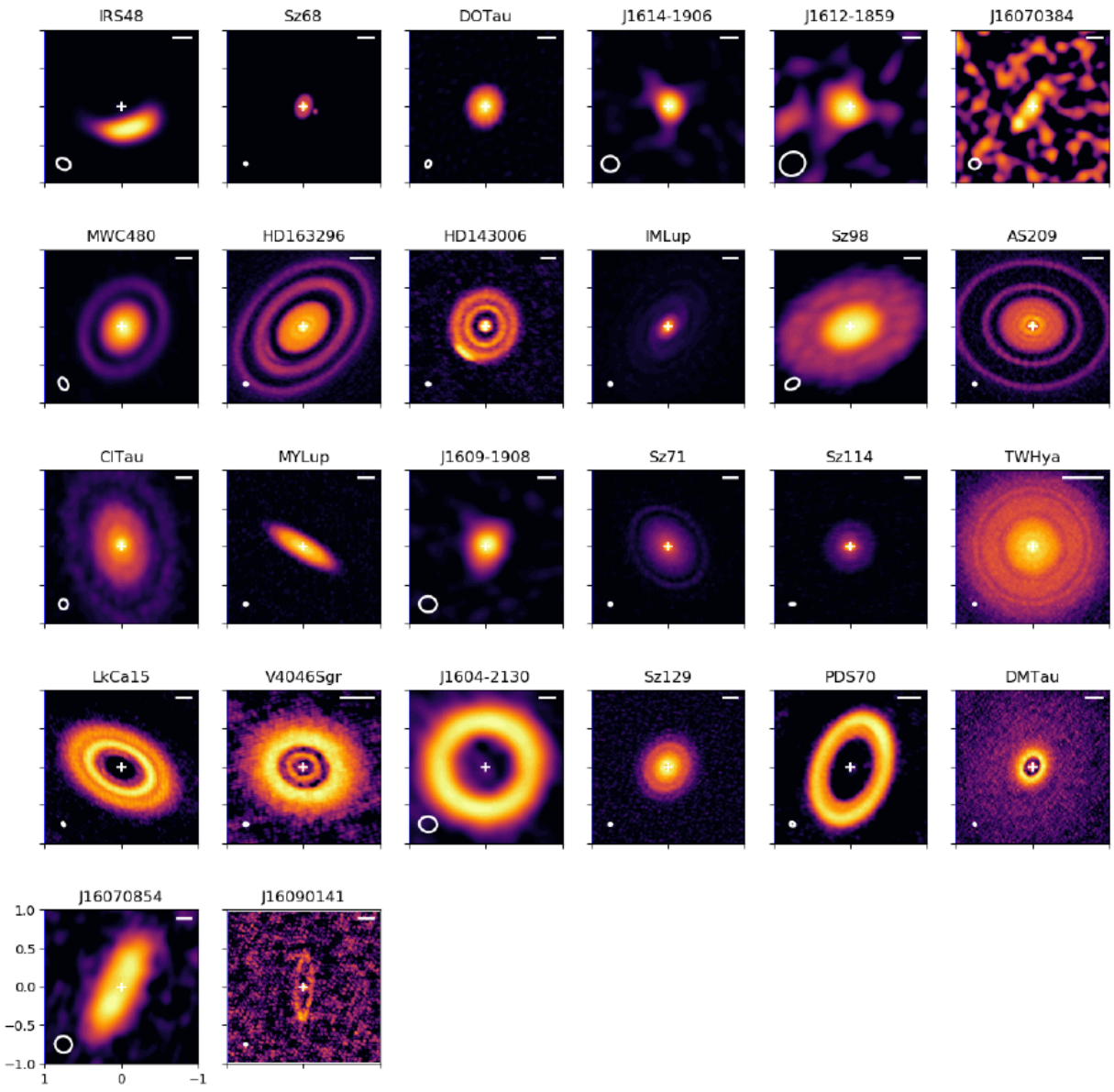
If you like C/O variations, you should have put a ring on it

Nienke van der Marel, Arthur Bosman, Sebastiaan Krijt, Gijs D. Mulders, Jennifer B. Bergner

The C/O-ratio as traced with C_2H emission in protoplanetary disks is fundamental for constraining the formation mechanisms of exoplanets and our understanding of volatile depletion in disks, but current C_2H observations show an apparent bimodal distribution which is not well understood, indicating that the C/O distribution is not described by a simple radial dependence. The transport of icy pebbles has been suggested to alter the local elemental abundances in protoplanetary disks, through settling, drift and trapping in pressure bumps resulting in a depletion of volatiles in the surface and an increase of the elemental C/O. We combine all disks with spatially resolved ALMA C_2H observations with high-resolution continuum images and constraints on the CO snowline to determine if the C_2H emission is indeed related to the location of the icy pebbles. We report a possible correlation between the presence of a significant CO-icy dust reservoir and high C_2H emission, which is only found in disks with dust rings outside the CO snowline. In contrast, compact dust disks (without pressure bumps) and warm transition disks (with their dust ring inside the CO snowline) are not detected in C_2H, suggesting that such disks may never have contained a significant CO ice reservoir. This correlation provides evidence for the regulation of the C/O profile by the complex interplay of CO snowline and pressure bump locations in the disk. These results demonstrate the importance of including dust transport in chemical disk models, for a proper interpretation of exoplanet atmospheric compositions, and a better understanding of volatile depletion in disks, in particular the use of CO isotopologues to determine gas surface densities.

- 原始惑星系円盤の C/O 比はどうなっているか
- 仮説: Pressure bump での氷ダスト集積により、volatile が減って C/O が上昇する
- この仮説を、観測的に検証する
  - 空間分解された C2H 観測・ダスト連続波分布・COスノーラインの制限を利用
  - C2H 放射が強い = C/O 比が大きい
- CO氷の reservoir と C2H 放射の強さに相関があることが示唆された
  - C2H で明るい円盤は、ダストリングが COスノーラインの外にある
  - コンパクト円盤や、ダストリングがCOスノーラインの内側にある円盤では、C2H 放射が観測されていない

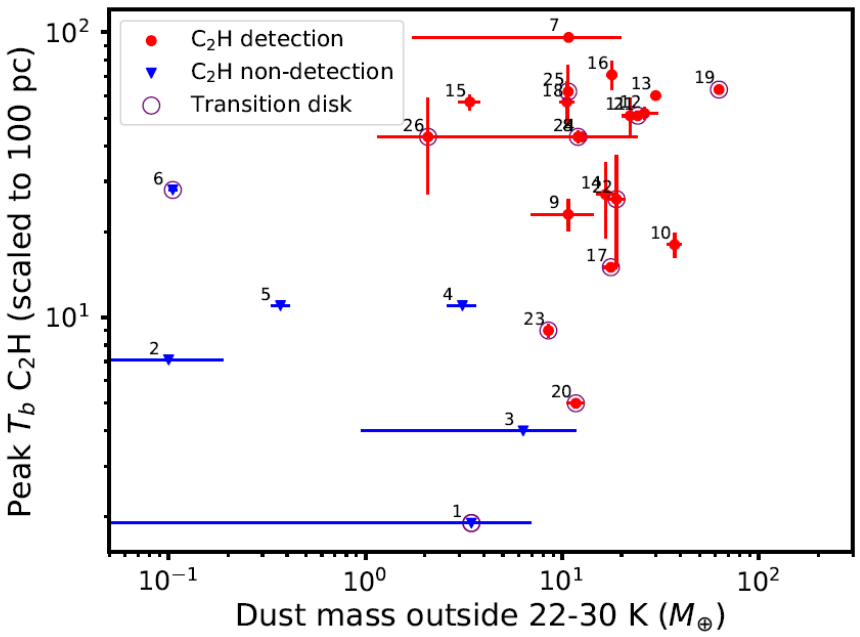
26天体のデータを使用、スケールバーが 30au

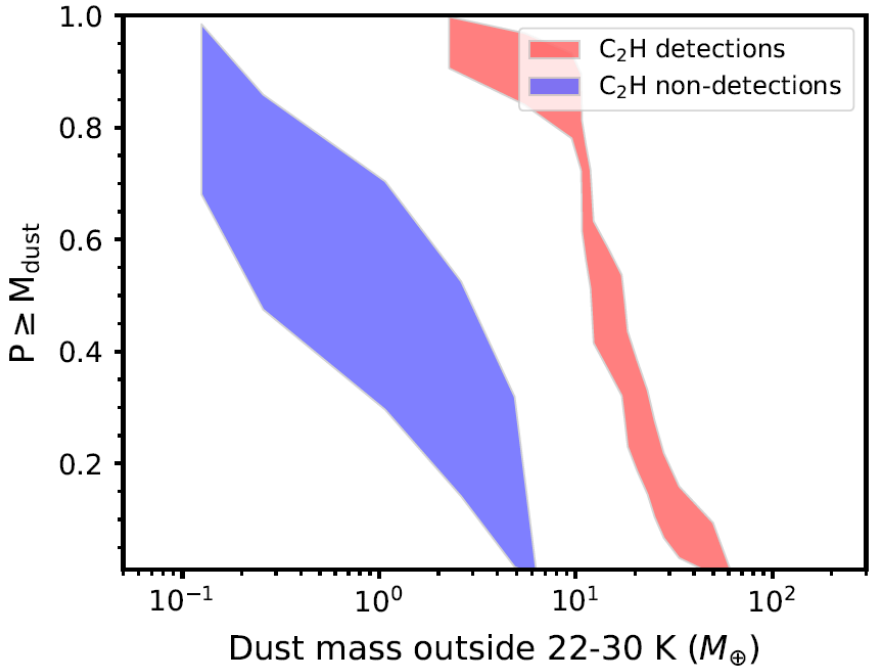


1行目： C2H 検出なし

2行目以降：
C2H 検出あり

CO氷の量（22-30K より温度の低い（中心星から遠い位置にある）ダストの質量）と、C2H の peak temperature の間の関係を調べる

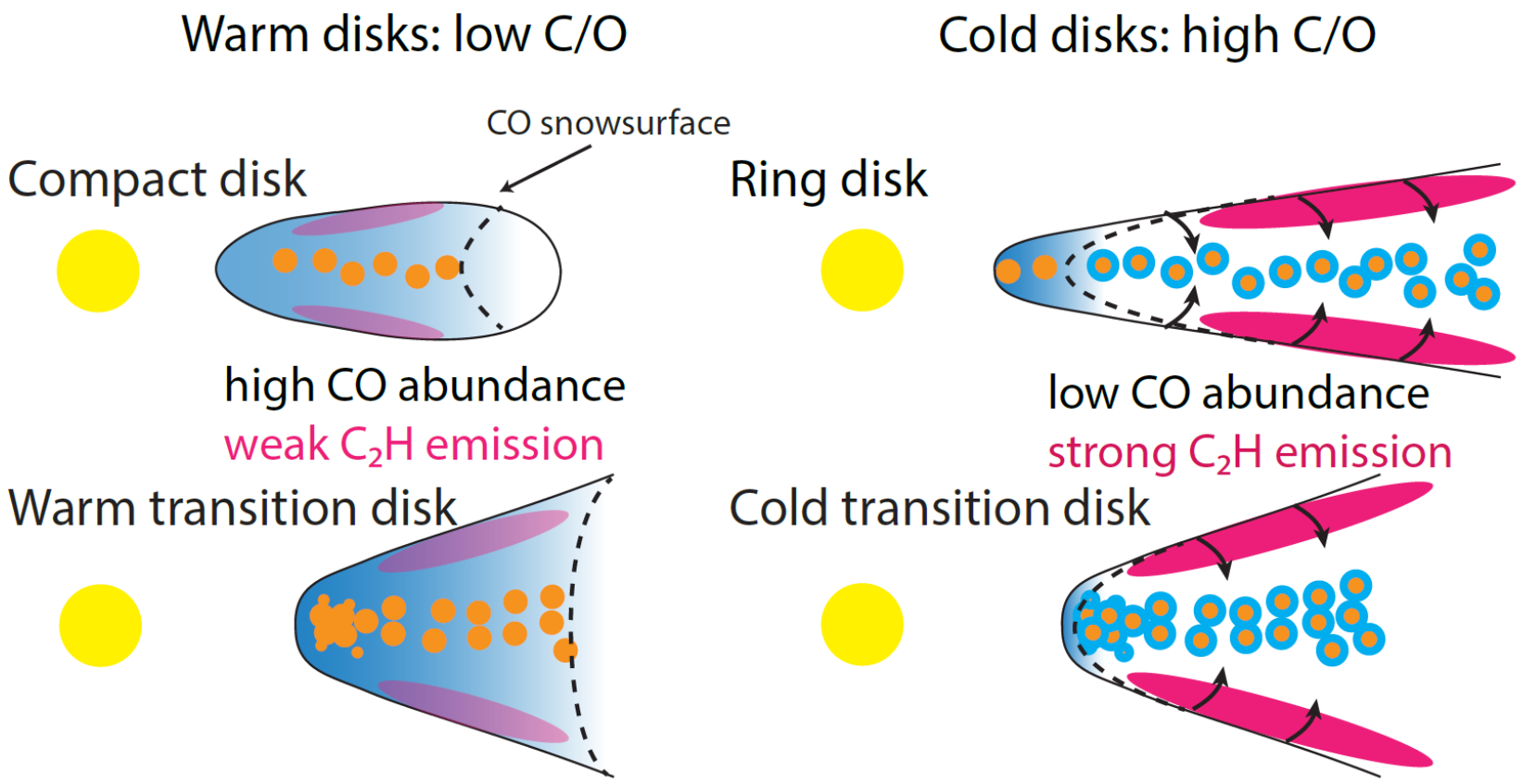




赤：C2H の検出されている天体
青：C2H の検出のない天体

C2H の検出の無い天体の方が、ダスト質量が小さい傾向にある。
- probability distribution function にすると、C2H 検出の有無で異なる分布

シナリオ



スノーラインの外側にダストが無い場合
- 基本的に、内側の CO 存在比は ISM と同じで、C2H の量も少ない

コンパクト円盤 or スノーライン内側にリング
例外：J16070384 ➔ そもそもミリ波放射が弱い

スノーラインの外側にリングがある場合
- pressure bump によってダストが滞留
- ダスト表面にたくさんの氷が吸着
- 氷の多くは O を含む（H2O, CO, CO2）
- よって、C/O 比が上がる
- 外側で、CO depletion も起こっている

No. 14

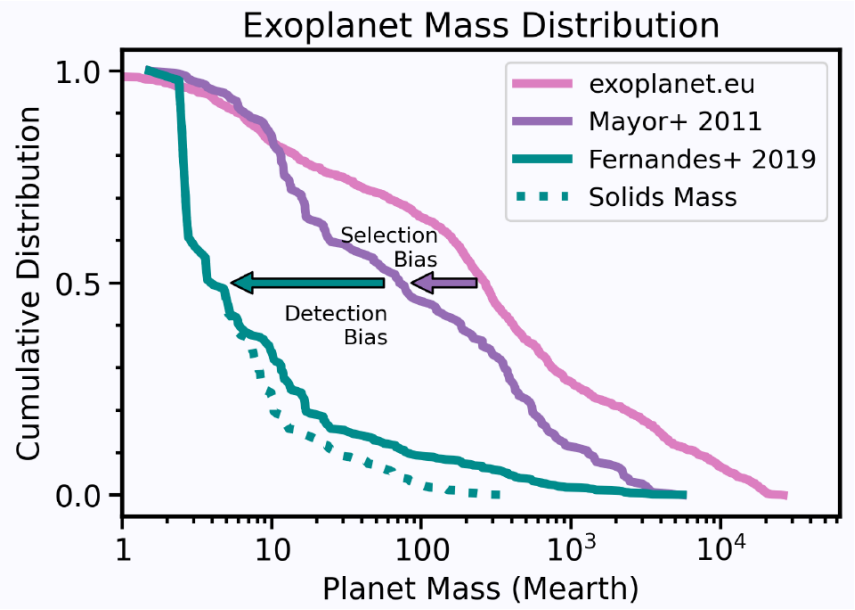
The Mass Budgets and Spatial Scales of Exoplanet Systems and Protoplanetary Disks

Gijs D. Mulders, Ilaria Pascucci, Fred J. Ciesla, Rachel B. Fernandes

Planets are born from disks of gas and dust, and observations of protoplanetary disks are used to constrain the initial conditions of planet formation. However, dust mass measurements of Class II disks with ALMA have called into question whether they contain enough solids to build the exoplanets that have been detected to date. In this paper, we calculate the mass and spatial scale of solid material around Sun-like stars probed by transit and radial velocity exoplanet surveys, and compare those to the observed dust masses and sizes of Class II disks in the same stellar mass regime. We show that the apparent mass discrepancy disappears when accounting for observational selection and detection biases. We find a discrepancy only when the planet formation efficiency is below 100%, or if there is a population of undetected exoplanets that significantly contributes to the mass in solids. We identify a positive correlation between the masses of planetary systems and their respective orbital periods, which is consistent with the trend between the masses and the outer radii of Class II dust disks. This implies that, despite a factor 100 difference in spatial scale, the properties of protoplanetary disks seem to be imprinted on the exoplanet population.

- 「円盤のダスト質量が惑星を作るのに足りない」問題の検討
- 視線速度法・トランジット法で見つかっている系外惑星の分布から導かれる固体質量が、Class II 円盤のダスト質量の分布と合うかを、太陽質量程度の星について、観測バイアスを考慮して検討
- 系外惑星系の固体質量分布は、円盤の固体質量の分布と一致する
  - つまり、「惑星の材料が足りない」問題は無く、これは観測バイアス（主に系外惑星系について）を考慮していなかったために見えていた
- 観測されている円盤の空間スケールは、系外惑星系の分布に比べて大きい
  - 外側の固体成分が、migration によって内側に運ばれつつ惑星が形成するというシナリオと整合的

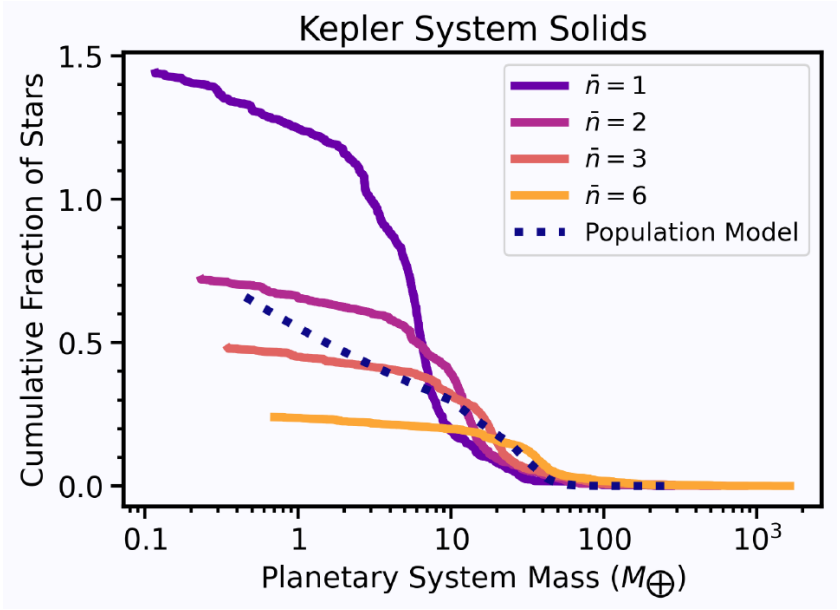
視線速度の惑星質量分布



ピンク：exoplanet.eu にリストされている全体
紫：HARPS による太陽型星の volume limited サーベイ
緑：観測バイアスの補正（点線が固体の分布）

軽い惑星ほど見つかりにくい
データに疑似惑星を injection することでバイアスを評価

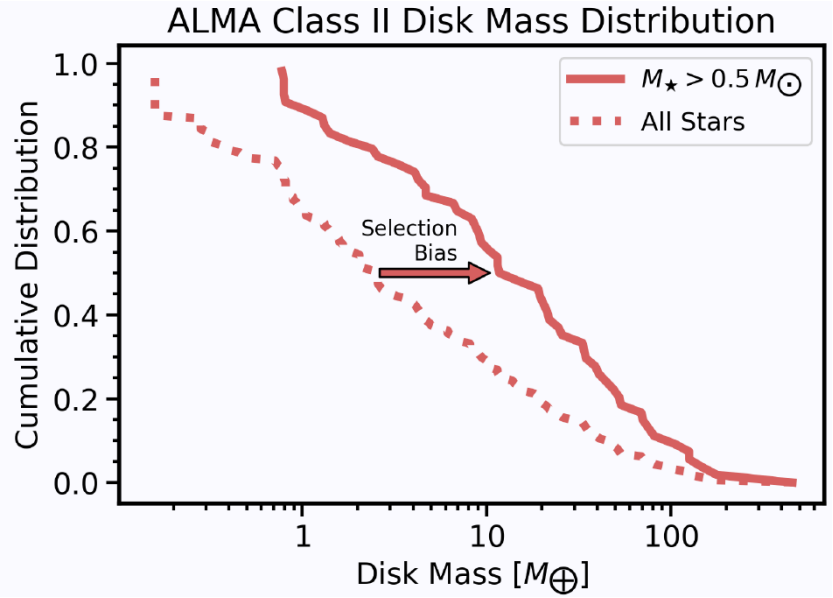
トランジット (Kepler) の惑星質量分布



トランジットでわかる、軌道半径の分布を、経験則に基づいて惑星質量分布に焼き直す

トランジットは、惑星数を間違えやすい。
➔ 別のモデルと比較して、一つの系が持っている惑星数を 3 と推定

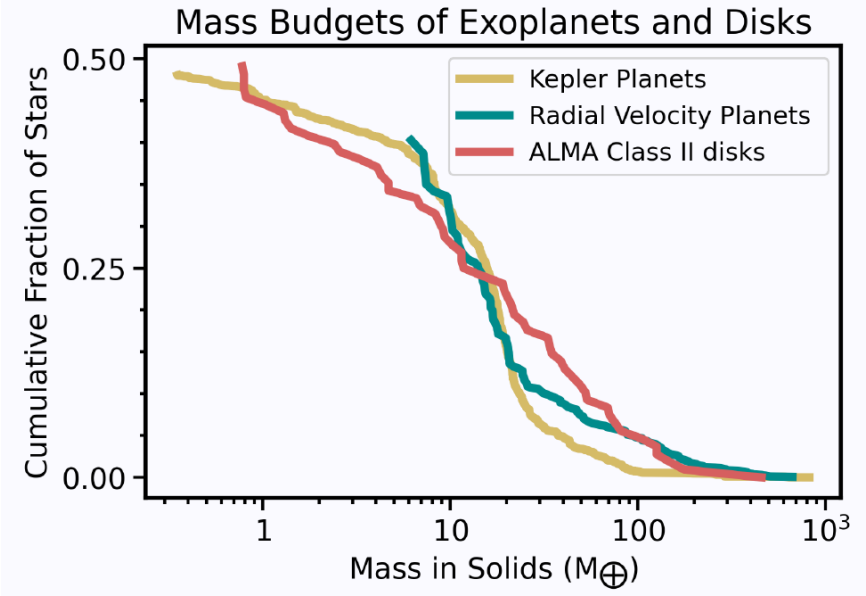
Class II 円盤の固体質量分布



Lupus と Chameleon I の円盤質量サーベイの結果について、太陽質量程度の星に限った分布を考える

円盤の観測は M型星が多いので、太陽質量付近（0.5-2 太陽質量）の星に限ると、典型的なダスト量は増加する

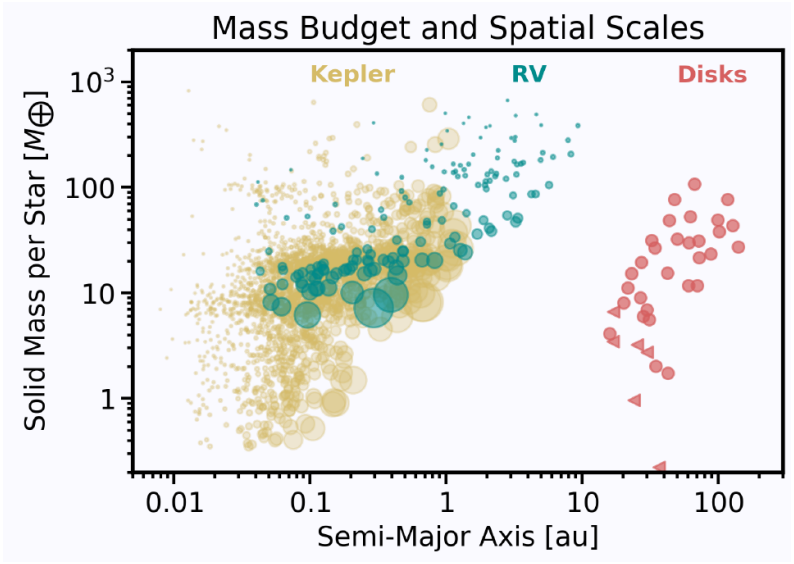
視線速度・トランジット・円盤の結果を比較

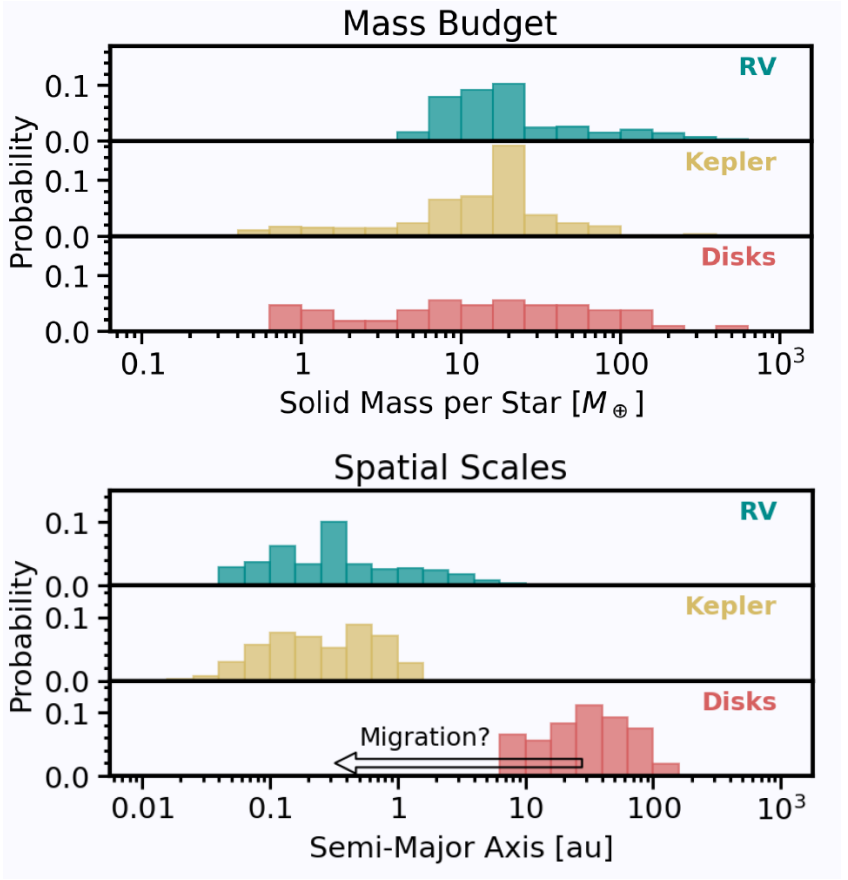


固体質量分布は、3つの場合で同じ

Class II 段階での固体質量と、系外惑星の質量がほぼ同じであることを示唆

空間スケールの違い

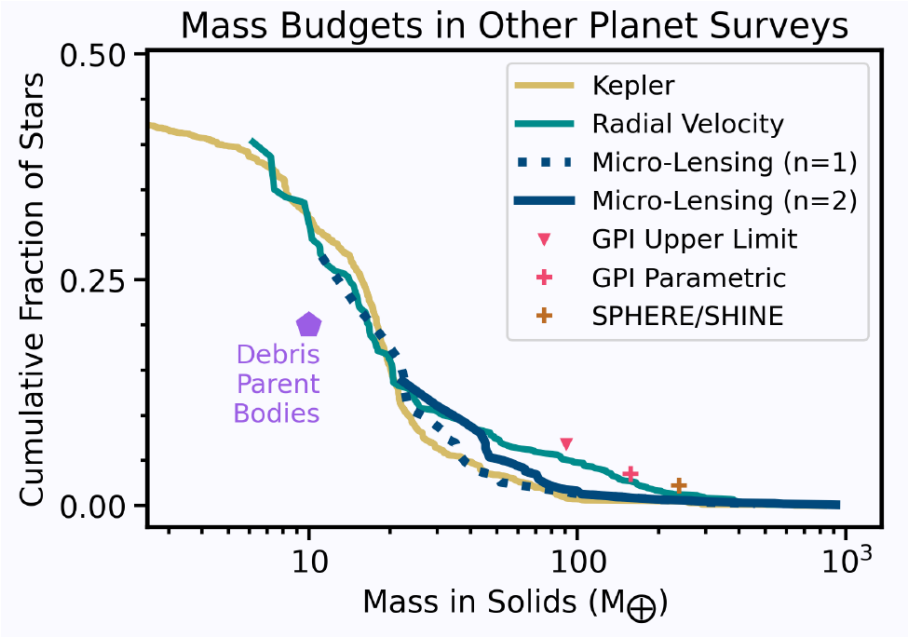


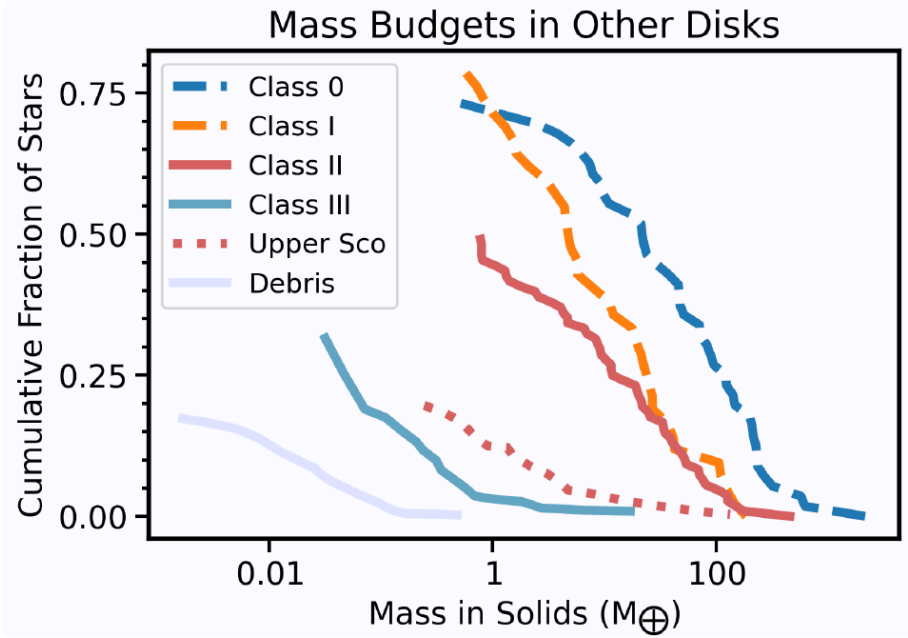


空間スケールは、円盤の方が大きい

➔ 外側の固体が、内側に移動して系外惑星になったシナリオを示唆

議論





- マイクロレンズの惑星は、バイアスを考慮するとほぼ同じような分布
- 直接撮像で見つかっている惑星もほぼ同じ分布の上に乗る
- デブリ円盤の固体の量は少ない
  - ただし、デブリ円盤系を惑星系と同等に扱えるかは分からない

- Class II の固体が全て惑星になったので、惑星形成の効率が良い？
- Class II より若い段階では、円盤はより massive なので、もともとの惑星の材料の量としては十分

No. 15

The IMF and multiplicity of stars from gravity, turbulence, magnetic fields, radiation and outflow feedback

Sajay Sunny Mathew, Christoph Federrath

We perform a series of three-dimensional, magnetohydrodynamical (MHD) simulations of star cluster formation including gravity, turbulence, magnetic fields, stellar radiative heating and outflow feedback. We observe that the inclusion of protostellar outflows (1) reduces the star formation rate by a factor of ~ 2, (2) increases fragmentation, and (3) shifts the initial mass function (IMF) to lower masses by a factor of 2.0 ± 0.2, without significantly affecting the overall shape of the IMF. The form of the sink particle (protostellar objects) mass distribution obtained from our simulations matches the observational IMFs reasonably well. We also show that turbulence-based theoretical models of the IMF agree well with our simulation IMF in the high-mass and low-mass regime, but do not predict any brown dwarfs, whereas our simulations produce a considerable number of sub-stellar objects, which are produced by dynamical interactions (ejections). We find that these dynamical interactions also play a key role for the binary separation distribution and stellar kinematics in general. Our numerical model of star cluster formation also reproduces the observed mass dependence of multiplicity. Our multiplicity fraction estimates generally concur with the observational estimates for different spectral types. We further calculate the specific angular momentum of all the sink particles and find that the average value of $1.5 \times 10^{19}\,\mathrm{cm^2\,s^{-1}}$ is consistent with observational data. The specific angular momentum of our sink particles lies in the range typical of protostellar envelopes and binaries. We conclude that the IMF is controlled by a combination of gravity, turbulence, magnetic fields, radiation and outflow feedback.

- 分子雲の collapse による星団形成の MHD シミュレーション
  - 星のフィードバック（輻射による加熱とアウトフロー）を入れる
- アウトフローにより、星形成率の低下・分裂の増加・IMF のピークの減少が起こる
- シミュレーションで出た IMF は、観測された IMF と良く似ている
  - ただし、ピークが 2 倍程度シミュレーションの方が大きい
- シミュレーションで出た IMF は、乱流の効果に基づいた理論的な IMF モデルと、高質量側で合う。低質量側では、シミュレーションで、褐色矮星がたくさんできた
- シミュレーション結果は、連星率の質量依存性の観測とも合う
- 星（sink 粒子）の角運動量も、観測と合う

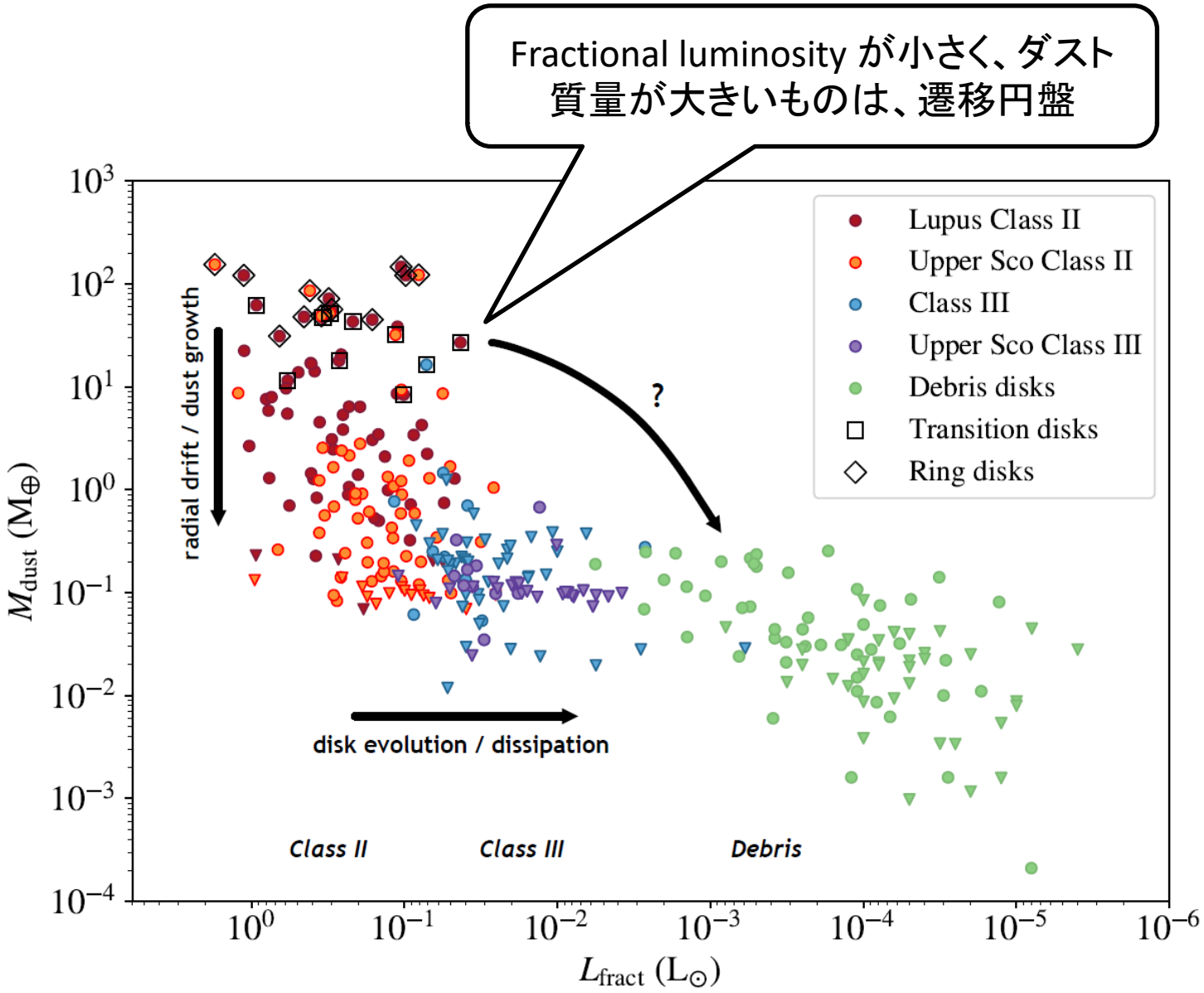
No. 16

Bridging the gap between protoplanetary and debris disks: separate evolution of millimeter and micrometer-sized dust

Arnaud Michel, Nienke van der Marel, Brenda Matthews

The connection between the nature of a protoplanetary disk and that of a debris disk is not well understood. Dust evolution, planet formation, and disk dissipation likely play a role in the processes involved. We aim to reconcile both manifestations of dusty circumstellar disks through a study of optically thin Class III disks and how they correlate to younger and older disks. In this work, we collect literature and ALMA archival millimeter fluxes for 85 disks (8%) of all Class III disks across nearby star-forming regions. We derive millimeter-dust masses $M_{\rm dust}$ and compare these with Class II and debris disk samples in the context of excess infrared luminosity, accretion rate, and age. The mean $M_{\rm dust}$ of Class III disks is $0.29 \pm 0.19\ M_{\oplus}$. We propose a new evolutionary scenario wherein radial drift is very efficient for non-structured disks during the Class II phase resulting in a rapid decrease of $M_{\rm dust}$. However, we find long infrared protoplanetary disk timescales of $\sim$8 Myr, which are consistent with overall slow disk evolution. In structured disks, the presence of dust traps allows for the formation of planetesimal belts at large radii, such as those observed in debris disks. We propose therefore that the planetesimal belts in debris disks are the result of dust traps in structured disks, whereas protoplanetary disks without dust traps decrease in dust mass through radial drift and are therefore undetectable as debris disks after the gas has dissipated. These results provide a hypothesis for a novel view of disk evolution.

- 近傍の星形成領域にある 85個の Class III 天体のミリ波フラックスから、ダスト質量を導出。Class II やデブリ円盤の結果と比較
  - Class III のダスト質量の平均は 0.29 地球質量
  - Class II 段階で構造の無い円盤は、ダストの radial drift が効いてダストがなくなる一方、リングを持つ天体は、Class III になってもダストがそこそこ残っている
- 赤外線で測った円盤の寿命は、8 Myr 程度と長いという示唆も得た
- 構造を持った円盤では、リングにトラップされたダスト（微惑星）が取り残され、デブリ円盤になるのではないか


Fractional luminosity が小さく、ダスト質量が大きいものは、遷移円盤
Lupus Class II
Upper Sco Class II
Class III
Upper Sco Class III
Debris disks
Transition disks
Ring disks
radial drift / dust growth
?
disk evolution / dissipation
Class II
Class III
Debris
M_{dust} ($M_\oplus$)
L_{fract} ($L_\odot$)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}

No. 17

Spatial Statistics in Star Forming Regions: Is Star Formation Driven By Column Density Alone?

Brendan Retter, Jennifer Hatchell, Tim Naylor

Star formation is known to occur more readily where more raw materials are available. This is often expressed by a 'Kennicutt-Schmidt' relation where the surface density of Young Stellar Objects (YSOs) is proportional to column density to some power, μ. The aim of this work was to determine if column density alone is sufficient to explain the locations of Class 0/I YSOs within Serpens South, Serpens Core, Ophiuchus, NGC1333 and IC348, or if there is clumping or avoidance that would point to additional influences on the star formation. Using the O-ring test as a summary statistic, 95 per cent confidence envelopes were produced for different values of μ from probability models made using the Herschel column density maps. The YSOs were tested against four distribution models: the best-estimate of μ for the region, $\mu = 0$ above a minimum column density threshold and zero probability elsewhere, $\mu = 1$, and the power-law that best represents the five regions as a collective, $\mu = 2.05 \pm 0.20$. Results showed that $\mu = 2.05$ model was consistent with the majority of regions and, for those regions, the spatial distribution of YSOs at a given column density is consistent with being random. Serpens South and NGC1333 rejected the $\mu = 2.05$ model on small scales of ~ 0.15pc which implies that small-scale interactions may be necessary to improve the model. On scales above 0.15 pc, the positions of YSOs in all five regions can be well described using column density alone.

- ガスの柱密度と YSO の数の関係（Kennicutt–Schmidt 則）を、5つの星形成領域で調べた
  - Serpens South, Serpence Core, Ophiuchus, NGC1333, IC348
- K-S law のベキの値が 2.05 のモデルでおおむね良い
- ただし、Serpens South と NGC1333 では、0.15pc より短いスケールで、ベキ2.05 のモデルが棄却された。
  - 小さなスケールでは、星形成は柱密度のみでは決まらないことが示唆された