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Testing the models of X-ray driven photoevaporation with accreting stars in the Orion Nebula Cluster

Stefan Flaischlen, Thomas Preibisch, Carlo Felice Manara, Barbara Ercolano

Context. Recent works highlight the importance of stellar X-rays on the evolution of the circumstellar disks of young stellar objects, especially for disk photoevaporation.
Aims. A signature of this process may be seen in the so far tentatively observed dependence of stellar accretion rates on X-ray luminosities. According to models of X-ray driven photoevaporation, stars with higher X-ray luminosities should show lower accretion rates, on average, in a sample with similar masses and ages.
Methods. To this aim, we have analyzed X-ray properties of young stars in the Orion Nebula Cluster determined with *Chandra* during the COUP observation as well as accretion data obtained from the photometric catalog of the *HST Treasury Program*. With these data, we have performed a statistical analysis of the relation between X-ray activity and accretion rates using partial linear regression analysis.
Results. The initial anticorrelation found with a sample of 332 young stars is considerably weaker compared to previous studies. However, excluding flaring activity or limiting the X-ray luminosity to the soft band (0.5 – 2.0 keV) leads to a stronger anticorrelation, which is statistically more significant. Furthermore, we have found a weak positive correlation between the higher component of the plasma temperature gained in the X-ray spectral fitting and the accretion rates, indicating that the hardness of the X-ray spectra may influence the accretion process.
Conclusions. There is evidence for a weak anticorrelation, as predicted by theoretical models, suggesting that X-ray photoevaporation modulates the accretion rate through the inner disk at late stages of disk evolution, leading to a phase of photoevaporation-starved accretion.

中心星のx線光度と円盤からの質量降着率の関係

光蒸発を考えると、x線光度が大きいほど降着率が小さいはず

Orion Nebula Cluster のyoung star 332天体で確かめる。

先行研究と比べると弱い反相関が得られたが、soft band (0.5-2.0KeV)だけで見ると

反相関がより強くなる。

背景

・円盤から中心星へのガス降着と、中心星からのX線放射は
星・円盤の進化を考える上で重要。
・降着のあるYSOsは降着がないYSOsよりX線光度が
低い傾向がある(Preibisch et al. 2005)。
・理論的解釈はいくつか考えられているが、X線光度が大きいと
光蒸発により降着率が減少する可能性が考えられる
(Ercolano & Pascucci 2017).

<u>X線光度と降着率の関係</u>
Drake et al. (2009)ではONCの39天体
Bustamante et al. (2016)ではONCの431天体
で、反相関が確かめられた。

しかし、先行研究の手法だと、反相関が出やすいバイアスがあった。
この論文では別の手法で先行研究の結果をチェック
・同程度の質量、年齢の星でX線光度と降着率の
反相関が見られるか検証
・フレアやX線スペクトル硬度の影響を調べる。

サンプルデータ

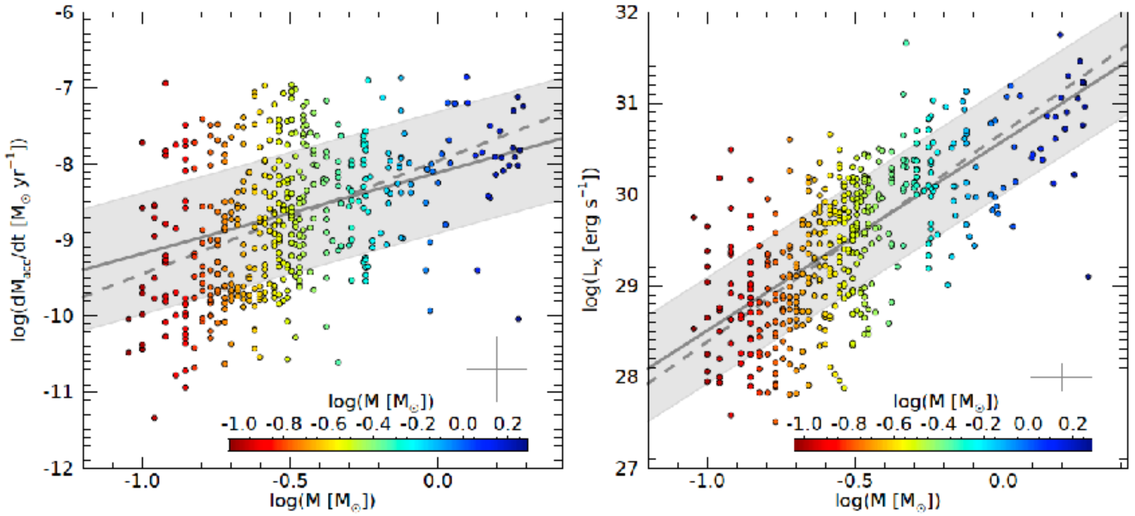
・ONCで先行研究から降着率と質量が
得られているものを選ぶ
・Gaia で距離が分かっているものに限定し、
距離が離れているものを除く。
・質量 0.2-2Msun,
年齢 5.5<log(τ [yr])<7.3に制限

↓

332天体

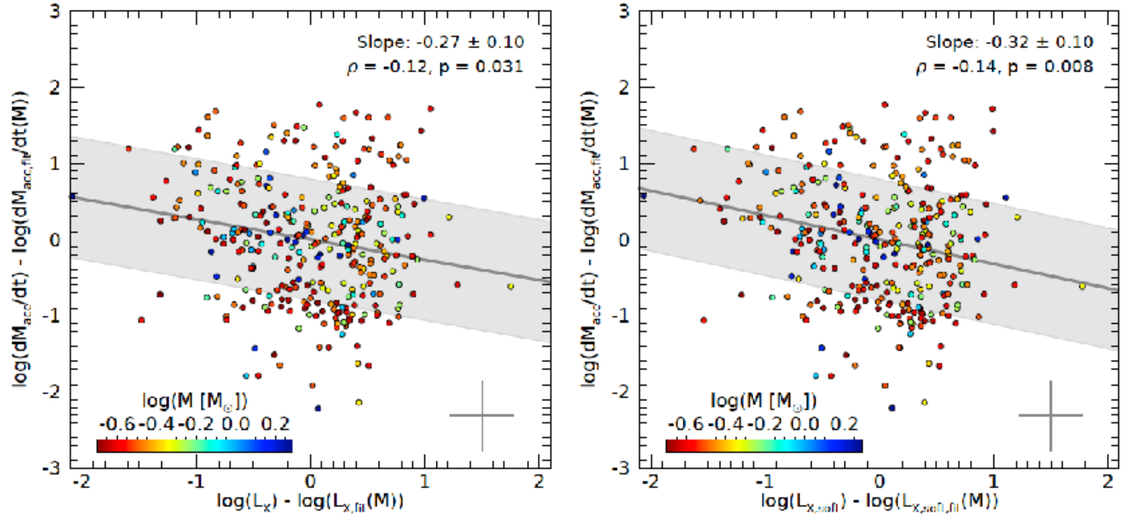
結果

質量降着率、Lxと星質量の相関



傾きなどは基本的に先行研究と整合的
サンプルの取り方には寄らない

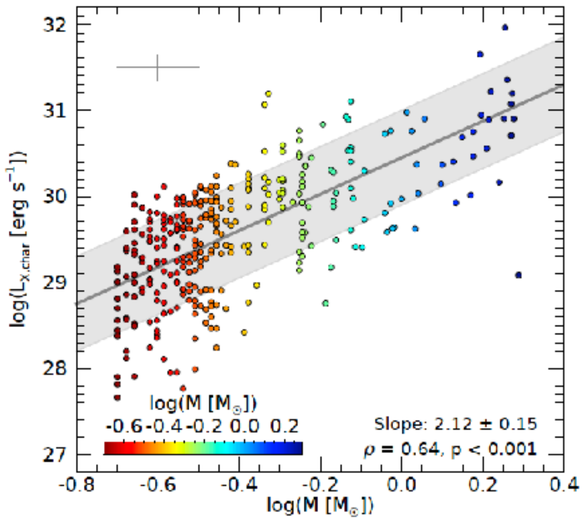
質量降着率とLxの相関

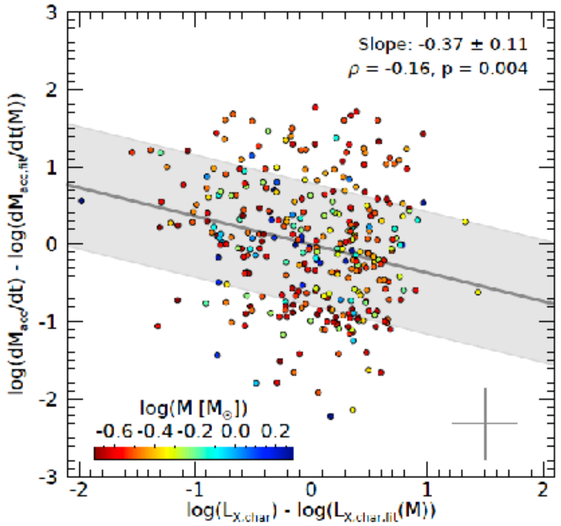


左：上図のfitting関数を引いた残差に対して相関をとる。
弱い反相関が得られる（傾きは星の進化モデルに依存）

右：Lx,soft (0.5-2.0keV)との相関
シミュレーションでは、<2.0keVが円盤風に寄与
より強い反相関が見える
星の進化モデルを変えても統計的に有意な反相関がでる

Lx,char(Lxから、flare による増光の寄与を除いたもの）の相関





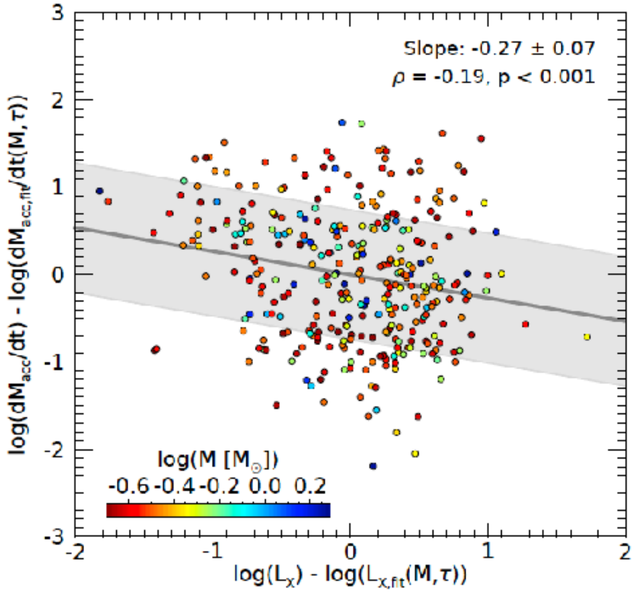
左：星質量との相関

右：Lx,char と降着率の相関

より強い相関が出る

（3D MHDシミュレーションでは、

フレアによって降着は増加/減少する場合がある。）



Lxの年齢に対する依存性も考慮して残差をとった場合の

Lxと降着率の相関。

より強い相関が見える。

（年齢の推定に関するモデルの不訂正がある。）

Disk Evolution Study Through Imaging of Nearby Young Stars (DESTINYS): Late infall causing disk misalignment and dynamic structures in SU Aur

C. Ginski, S. Facchini, J. Huang, M. Benisty, D. Vaendel, L. Stapper, C. Dominik, J. Bae, F. Menard, G. Muro-Arena, M. Hogerheijde, M. McClure, R. G. van Holstein, T. Birnstiel, Y. Boehler, A. Bohn, M. Flock, E. E. Mamajek, C. F. Manara, P. Pinilla, C. Pinte, A. Ribas

Gas-rich circumstellar disks are the cradles of planet formation. As such, their evolution will strongly influence the resulting planet population. In the ESO DESTINYS large program, we study these disks within the first 10 Myr of their development with near-infrared scattered light imaging.
Here we present VLT/SPHERE polarimetric observations of the nearby class II system SU Aur in which we resolve the disk down to scales of ∼ 7 au. In addition to the new SPHERE observations, we utilize VLT/NACO, HST/STIS and ALMA archival data.
The new SPHERE data show the disk around SU Aur and extended dust structures in unprecedented detail. We resolve several dust tails connected to the Keplerian disk. By comparison with ALMA data, we show that these dust tails represent material falling onto the disk. The disk itself shows an intricate spiral structure and a shadow lane, cast by an inner, misaligned disk component.
Our observations suggest that SU Aur is undergoing late infall of material, which can explain the observed disk structures. SU Aur is the clearest observational example of this mechanism at work and demonstrates that late accretion events can still occur in the class II phase, thereby significantly affecting the evolution of circumstellar disks. Constraining the frequency of such events with additional observations will help determine whether this process is responsible for the spin-orbit misalignment in evolved exoplanet systems.

SU Aur (class II) のVLT/SPHERE での偏光観測（分解能~7 au）
円盤につながる複数のdust tail. 円盤に落下する物体。
円盤には渦状腕と、内側のmisaligned disk による影が見える。
SU Aur は降着の終盤を見ている。

背景

近年の散乱光の観測で、円盤の内側と外側で
misalignしている円盤が観測されている。

misaligned disk の起源として、
・伴星や惑星と円盤の相互作用
・降着による角運動量輸送

これらを検証するには、大小両方の
空間スケールの観測が重要。

SU Aurは良いサンプル
距離 158.4+-1.5 pc, classical T Tauri
log(L/Lsun)=0.9, 質量~2.0Msun,
年齢4-5.5Myr
500 au の非対称な構造が付随
西にダストテイルが散乱光で観測
ALMAで西側に数百auのガステイルが観測

DESTINYS program の結果を、
VLT/NACO, HST/STIS, ALMA の観測と合わせて紹介する。

結果

円盤について

<u>dark lane</u>

円盤に影が見える(中央)

近赤外干渉計で見えた inner disk （左）

inclination angle 52.8° 西が手前

→incline したinner disk の影

2011, 2014, 2019年の観測で動いていないので、

伴星ではない

<u>明るさの非対称</u>

北東が明るい。

ALMA観測からposition angle122.9°

北東が手前なら前方散乱で説明できる。

影の説明とも整合的

<u>渦構造 (右)</u>

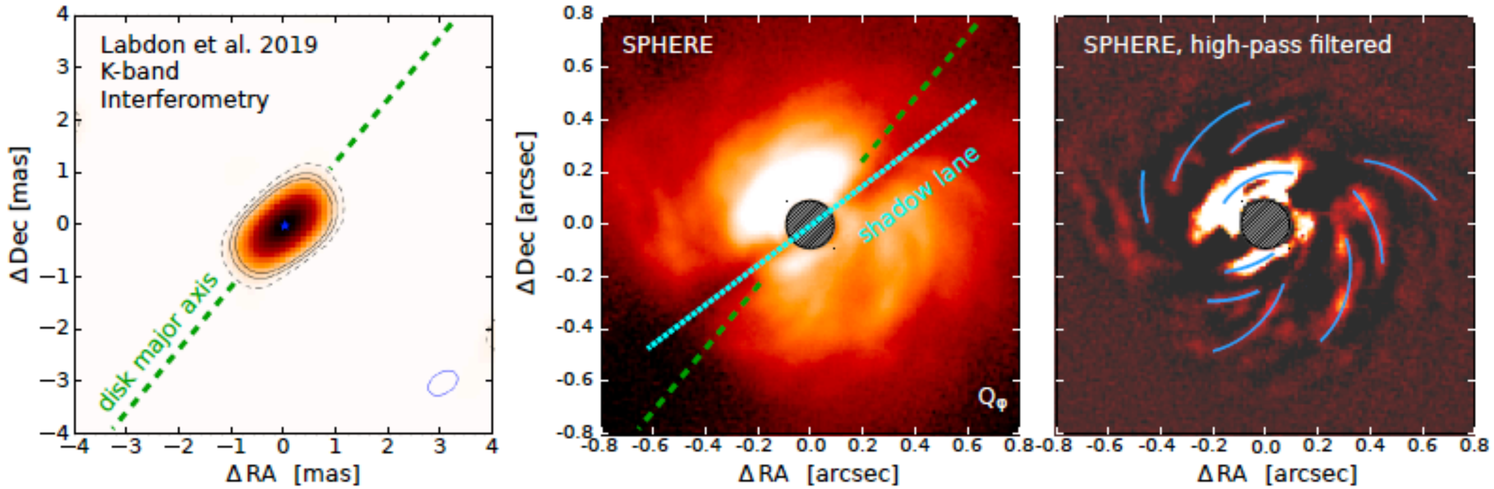
南西に6本 (pitch angle 25°-49°)

北東に4本 (pitch angle 7°-22°)

北東が手前なら、projection で理解できる。

ガス降着によって引き起こされる

不安定性起源か。



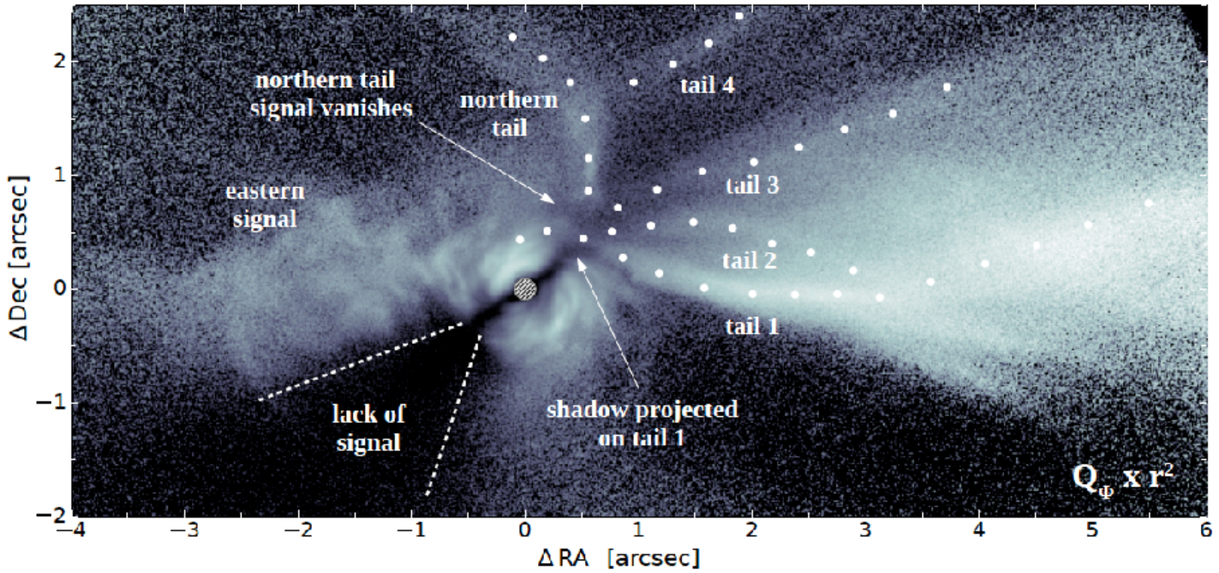
結果

エンベロープについて

dark lane がtailまで伸びている

tail が手前から円盤に降着している場合、

影の角度の変化を説明できる。



northern tail:

他の4本より暗く、向きが異なる。

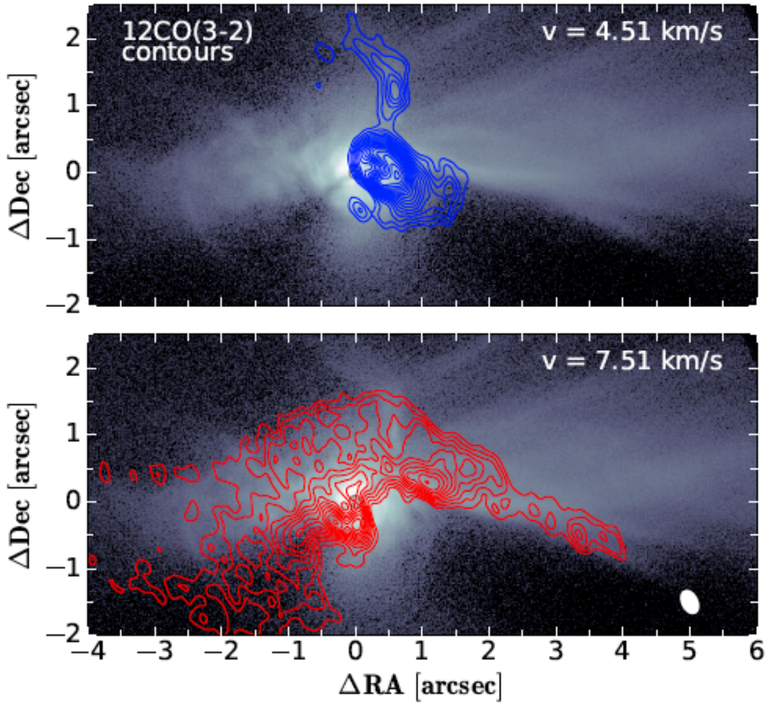
円盤付近で暗くなる

→円盤に裏側から降着

後方散乱で暗くなることと整合的。

ALMAの12COでも、tail 1 はred shift,

northern tail は blue shift していて整合的



13COの結果から、tail は円盤の傾きを変えるだけの

角運動量を持てるくらいはmassive

Tail 1 はAB Aurの方向に伸びている。

二つは連星で、tailは二つをつなぐ構造？

11

The Anatomy of an Unusual Edge-on Protoplanetary Disk. II. Gas temperature and a warm outer region

Christian Flores, Gaspard Duchene, Schuyler Wolff, Marion Villenave, Karl Stapelfeldt, Jonathan P. Williams, Christophe Pinte, Deborah Padgett, Michael S. Connelley, Gerrit van der Plas, Francois Menard, Marshall D. Perrin

We present high-resolution ^{12}CO and ^{13}CO 2–1 ALMA observations, as well as optical and near-infrared spectroscopy, of the highly-inclined protoplanetary disk around SSTC2D J163131.2-242627. The spectral type we derive for the source is consistent with a 1.2 $M_\odot$ star inferred from the ALMA observations. Despite its massive circumstellar disk, we find little to no evidence for ongoing accretion on the star. The CO maps reveal a disk that is unusually compact along the vertical direction, consistent with its appearance in scattered light images. The gas disk extends about twice as far away as both the submillimeter continuum and the optical scattered light. CO is detected from two surface layers separated by a midplane region in which CO emission is suppressed, as expected from freeze-out in the cold midplane. We apply a modified version of the Topographically Reconstructed Distribution method presented by Dutrey et al. (2017) to derive the temperature structure of the disk. We find a temperature in the CO-emitting layers and the midplane of ~33 K and ~20 K at R < 200 au, respectively. Outside of R > 200 au, the disk's midplane temperature increases to ~30 K, with a nearly vertically isothermal profile. The transition in CO temperature coincides with a dramatic reduction in the sub-micron and sub-millimeter emission from the disk. We interpret this as interstellar UV radiation providing an additional source of heating to the outer part of the disk.

ALMAによるedge on 天体SSTC2D J163131…の高分解能観測 (12CO, 13CO 2-1)

質量1.2Msun、円盤はmassiveだが星への降着の証拠は得られたかった。

CO map で垂直方向にコンパクトな分布が得られた。ガス円盤は連続波や散乱項と比べて2倍広がっている。

COがfreaze-out する赤道面では見えず、表面からの放射が見えている。

円盤の温度構造をモデル計算、r<200 auで表面が~33K、赤道面が~20K, r>200 auでは~30Kでほぼ等温

外部からのUVradiation が原因か。

Physical and Chemical Structure of the Disk and Envelope of the Class 0/I Protostar L1527

Lizxandra Flores-Rivera, Susan Terebey, Karen Willacy, Andrea Isella, Neal Turner, Mario Flock

Sub-millimeter spectral line and continuum emission from the protoplanetary disks and envelopes of protostars are powerful probes of their structure, chemistry, and dynamics. Here we present a benchmark study of our modeling code, RadChemT, that for the first time uses a chemical model to reproduce ALMA $C^{18}O$ (2-1) and CARMA ^{12}CO (1-0) and N_2H^+ (1-0) observations of L1527, that allow us to distinguish the disk, the infalling envelope and outflow of this Class 0/I protostar. RadChemT combines dynamics, radiative transfer, gas chemistry and gas-grain reactions to generate models which can be directly compared with observations for individual protostars. Rather than individually fit abundances to a large number of free parameters, we aim to best match the spectral line maps by (i) adopting a physical model based on density structure and luminosity derived primarily from previous work that fit SED and 2D imaging data, updating it to include a narrow jet detected in CARMA and ALMA data near ($\leq$ 75au) the protostar, and then (ii) computing the resulting astrochemical abundances for 292 chemical species.

Our model reproduces the $C^{18}O$ and N_2H^+ line strengths within a factor of 3.0; this is encouraging considering the pronounced abundance variation (factor $> 10^3$) between the outflow shell and CO snowline region near the midplane. Further, our modeling confirms suggestions regarding the anti-correlation between N_2H^+ and the CO snowline between 400 au to 2,000 au from the central star. Our modeling tools represent a new and powerful capability with which to exploit the richness of spectral line imaging provided by modern submillimeter interferometers.

著者らのモデル計算コードRadChemTをClass 0/I 天体のL1527に適用、ALMAのC18O(2-1), CARMA 12CO(1-0), N2H+(1-0)の観測を再現し、円盤、envelope, outflowの寄与を区別する。
SEDや2D imageのfitting から光度と密度構造を推定し、その後化学組成を計算する。
C18OとN2H+が factor 3の誤差で一致

ALMA-IRDC II. First high-angular resolution measurements of the 14N/15N ratio in a large sample of infrared-dark cloud cores

F. Fontani, A. T. Barnes, P. Caselli, J. D. Henshaw, G. Cosentino, I. Jiménez-Serra, J. C. Tan, J. E. Pineda, C. Y. Law

The $^{14}N/^{15}N$ ratio in molecules exhibits a large variation in star-forming regions, especially when measured from N_2H^+ isotopologues. However, there are only a few studies performed at high-angular resolution. We present the first interferometric survey of the $^{14}N/^{15}N$ ratio in N_2H^+ obtained with Atacama Large Millimeter Array observations towards four infrared-dark clouds harbouring 3 mm continuum cores associated with different physical properties. We detect $N^{15}NH^+$ (1–0) in ~ 20 – 40% of the cores, depending on the host cloud. The $^{14}N/^{15}N$ values measured towards the millimeter continuum cores range from a minimum of ~ 80 up to a maximum of ~ 400. The spread of values is narrower than that found in any previous single-dish survey of high-mass star-forming regions, and than that obtained using the total power data only. This suggests that the $^{14}N/^{15}N$ ratio is on average higher in the diffuse gaseous envelope of the cores, and stresses the need for high-angular resolution maps to measure correctly the $^{14}N/^{15}N$ ratio in dense cores embedded in IRDCs. The average $^{14}N/^{15}N$ ratio of ~ 210 is also lower than the interstellar value at the Galactocentric distance of the clouds (~ 300 – 330), although the sensitivity of our observations does not allow us to unveil $^{14}N/^{15}N$ ratios higher than ~ 400. No clear trend is found between the $^{14}N/^{15}N$ ratio and the core physical properties. We find only a tentative positive trend between $^{14}N/^{15}N$ and H_2 column density. However, firmer conclusions can be drawn only with higher sensitivity measurements.

14N/15Nの高分解能観測。ALMAを用いて4つのinfrared-dark cloudsを観測

3mm continuum core で14N/15N=80-400。幅は単一鏡での大質量星形成領域の観測よりも小さい。

平均として、エンベロープの方が14N/15Nが大きい。コアでの値を知るには高分解能が必要。

コアの物理状態との相関は見られない。

15

K-band High-Resolution Spectroscopy of Embedded Massive Protostars

Tien-Hao Hsieh, Michihiro Takami, Michael S. Connelley, Sheng-Yuan Liu, Yu-Nung Su, Naomi Hirano, Motohide Tamura, Masaaki Otsuka, Jennifer L. Karr, Tae-Soo Pyo

A classical paradox in high-mass star formation is that powerful radiation pressure can halt accretion, preventing further growth of a central star. Disk accretion has been proposed to solve this problem, but the disks and the accretion process in high-mass star formation are poorly understood. We executed high-resolution (R=35,000-70,000) iSHELL spectroscopy in K-band for eleven high-mass protostars. Br-γ emission was observed toward eight sources, and the line profiles for most of these sources are similar to those of low-mass PMS stars. Using an empirical relationship between the Br-γ and accretion luminosities, we tentatively estimate disk accretion rates ranging from $\lesssim 10^{-8}$ and $\sim 10^{-4}$ $M_{\odot}$ yr^{-1}. These low-mass-accretion rates suggest that high-mass protostars gain more mass via episodic accretion as proposed for low-mass protostars. Given the detection limits, CO overtone emission (v=2-0 and 3-1), likely associated with the inner disk region ($r \ll 100$ au), was found towards two sources. This low-detection rate compared with Br-γ emission is consistent with previous observations. Ten out of the eleven sources show absorption at the v=0-2 R(7) – R(14) CO R-branch. Most of them are either blueshifted or redshifted, indicating that the absorption is associated with an outflow or an inflow with a velocity of up to $\sim$ 50 km s^{-1}. Our analysis indicates that the absorption layer is well thermalized (and therefore $n_{\mathrm{H_2}} \gtrsim 10^6$ cm^{-3}) at a single temperature of typically 100-200 K, and located within 200-600 au of the star.

大質量原始星のKバンドでのスペクトル観測（iSHELL）

8天体でBr-γが観測 low-mass PMS starと似ている。

Br-γから降着率を推定 10^-8~10^-4Msun/yr 程度、episodic accretion で質量を得ているか。

outflowか inflow による吸収が見える。

A pebble accretion model for the formation of the terrestrial planets in the Solar System

Anders Johansen, Thomas Ronnet, Martin Bizzarro, Martin Schiller, Michiel Lambrechts, Åke Nordlund, Helmut Lammer

Pebbles of millimeter sizes are abundant in protoplanetary discs around young stars. Chondrules inside primitive meteorites – formed by melting of dust aggregate pebbles or in impacts between planetesimals – have similar sizes. The role of pebble accretion for terrestrial planet formation is nevertheless unclear. Here we present a model where inwards-drifting pebbles feed the growth of terrestrial planets. The masses and orbits of Venus, Earth, Theia (which later collided with the Earth to form the Moon) and Mars are all consistent with pebble accretion onto protoplanets that formed around Mars' orbit and migrated to their final positions while growing. The isotopic compositions of Earth and Mars are matched qualitatively by accretion of two generations of pebbles, carrying distinct isotopic signatures. Finally, we show that the water and carbon budget of Earth can be delivered by pebbles from the early generation before the gas envelope became hot enough to vaporise volatiles.

中心星落下するペブルによる地球型惑星の成長についての計算。
金星、地球、テイア、火星の軌道、質量は、火星軌道周辺で形成されたペブルの原始惑星への降着と整合的。
二世代のペブルが降着するとすると、地球と火星については同位体比も定性的に合う。
地球の水、炭素量は、第一世代のペブルから供給できる。