星形成ゼミ

#356 16-22

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Time-dependent, long-term hydrodynamic simulations of the inner protoplanetary disk II: The importance of stellar rotation

Lukas Gehrig, Daniel Steiner, Eduard Vorobyov, Manuel Güdel ★ The spin evolution of young protostars, surrounded by an accretion disk, still poses problems for observations and theoretical models. In recent studies, the importance of the magnetic star-disk interaction for stellar spin evolution has been elaborated. The accretion disk in these studies, however, is only represented by a simplified model and important features are not considered. We combined the implicit hydrodynamic TAPIR disk code with a stellar spin evolution model. The influence of stellar magnetic fields on the disk dynamics, the radial position of the inner disk radius, as well as the influence of stellar rotation on the disk were calculated self-consistently. Within a defined parameter space, we can reproduce the majority of fast and slow rotating stars observed in young stellar clusters. Additionally, the back reaction of different stellar spin evolutionary tracks on the disk can be analyzed. Disks around fast rotating stars are located closer to the star. Consequently, the disk midplane temperature in the innermost disk region increases significantly compared to slow rotating stars. We can show the effects of stellar rotation on episodic accretion outbursts. The higher temperatures of disks around fast rotating stars result in more outbursts and a longer outbursting period over the disk lifetime. The combination of a long-term hydrodynamic disk and a stellar spin evolution model allows the inclusion of previously unconsidered effects such as the back-reaction of stellar rotation on the long-term disk evolution and the occurrence of accretion outbursts. However, a wider parameter range has to be studied to further investigate these effects. Additionally, a possible interaction between our model and a more realistic stellar evolution code (e.g., the MESA code) can improve our understanding of the stellar spin evolution and its effects on the pre-main sequence star.

- 星の角運動量進化：star-disk相互作用が重要
- Hydrodynamic TAPIR disk code with a stellar spin model
  - Diskにおける星磁場の影響，円盤の内縁半径，星回転進化を整合的に解く
- 高棹さんが最近、星と円盤の磁場を介した相互作用のシミュレーション論文を出したので参照のこと

The effect of metallicity on the abundances of molecules in protoplanetary disks

R. Guadarrama, Eduard I. Vorobyov, Christian Rab, Manuel Güdel ★ We study the influence of different metallicities on the physical, thermal, and chemical properties of protoplanetary disks, and in particular on the formation and destruction of carbon-based molecules. With the thermo-chemical code ProoDIMO we investigate the impact of lower metallicities on the radiation field, disk temperature, and the abundance of different molecules (H_2O, CH_4, CO, CO_2, HCN, CN, HCO^+ and N_2H^+). We use a fiducial disk model as a reference model and produce two models with lower metallicity. The resulting influence on different chemical species is studied by analyzing their abundance distribution throughout the disk and their vertical column density. Furthermore, the formation and destruction reactions of the chemical species are studied. The results show a relation between the metallicity of the disk and the strength of the stellar radiation field inside the disk. As the metallicity decreases the radiation field is able to penetrate deeper regions of the disk. As a result, there is a stronger radiation field overall in the disk with lower metallicity which also heats up the disk. This triggers a series of changes in the chemical formation and destruction efficiencies for different chemical species. In most cases, the available species abundances change and have greater values compared to scaled-down abundances by constant factors. Metallicity has a clear impact on the snowline of the molecules studied here as well. As metallicity decreases the snowlines are pushed further out and existing snow rings shrink in size.

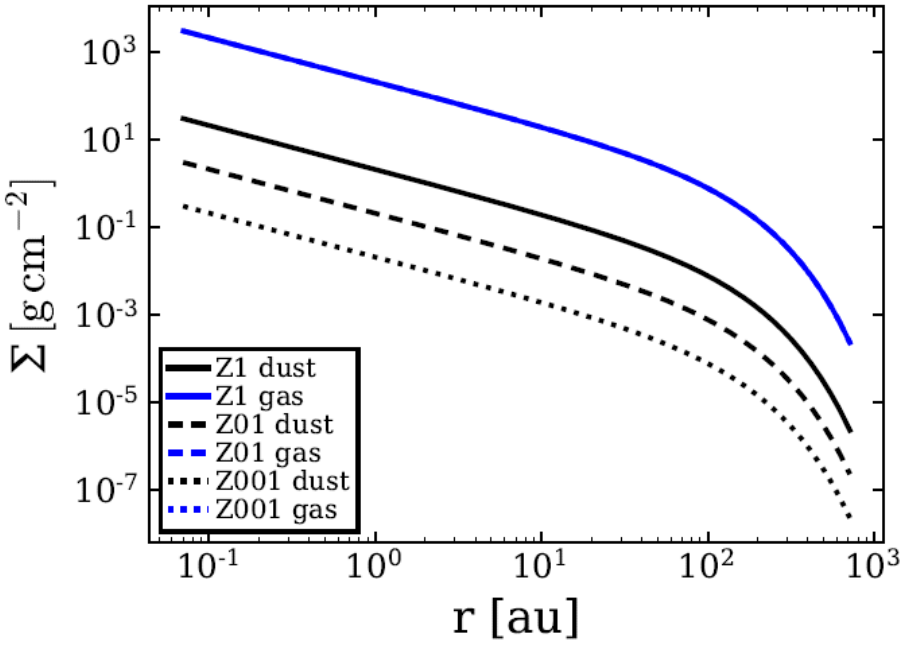
- 背景
  - これまでの原始惑星系円盤の化学モデルは太陽金属量を基にしたものが主
  - 観測的にはいくつかの量について金属量依存性があることが知られている。
    - マゼラン雲の観測 → mass accretion rateは金属量に反比例 (De Marchi+2013)
    - 銀河外縁部観測 → 低金属量の方が短い寿命 (Yasui+2010,2016, 理論Nakatani+2018)
  - 金属量の違いがどのように化学構造に依存するかは未解明

手法とモデル

- Radiation thermo-chemical code PRODIMO (Woit
  - Radiation transfer of stellar and background radiation
  - Steady-state chemical network (Kamp+2017)
  - Various kinds of heating and cooling processes.
- モデル
  - 中心星：M=0.7Msun, T=4000K, L=Lsun, Lx=2.6e-4Lsun
  - 金属量　Z1 = 0.85Zsun (standard T Tauri in the code), Z01 = 0.1Z1, Z001 = 0.01Z1
  - Dust-to-gas mass ratio decreases in proportion to the metallicity
  - Dust disk structure
    - Size distribution amin=0.05 um, amax=3000um, f(a) ∝ a^-3.5
    - Composition 60% amorphous lab. Silicate, 15% amorphous carbon, 25% vacuum.

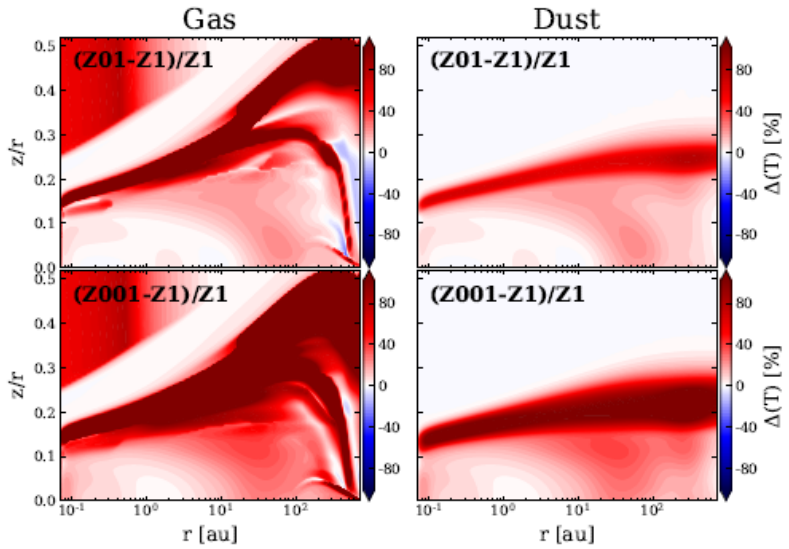
Table 2: Variations of the model used in this study. The columns represent the disk gas mass, metallicity, and dust-to-gas ratio.

Model	$M_{\rm disk}$ [$M_\odot$]	Z [$Z_\odot$]	dust-to-gas ratio
Z1	3.0×10^{-2}	8.5×10^{-1}	1.0×10^{-2}
Z01	3.0×10^{-2}	8.5×10^{-2}	1.0×10^{-3}
Z001	3.0×10^{-2}	8.5×10^{-3}	1.0×10^{-4}



温度構造と輻射場の金属量依存性

- **温度構造**
  - 金属量の低下は、特に円盤表層の領域の
    ダストとガスの温度を上昇させる。



- **UV輻射場**
  - χ: 920um～2400umの
    habing fluxで規格化したflux
  - Dust減光量が減るために,
    金属量が小さい方が、
    円盤の奥までUVが到達できる

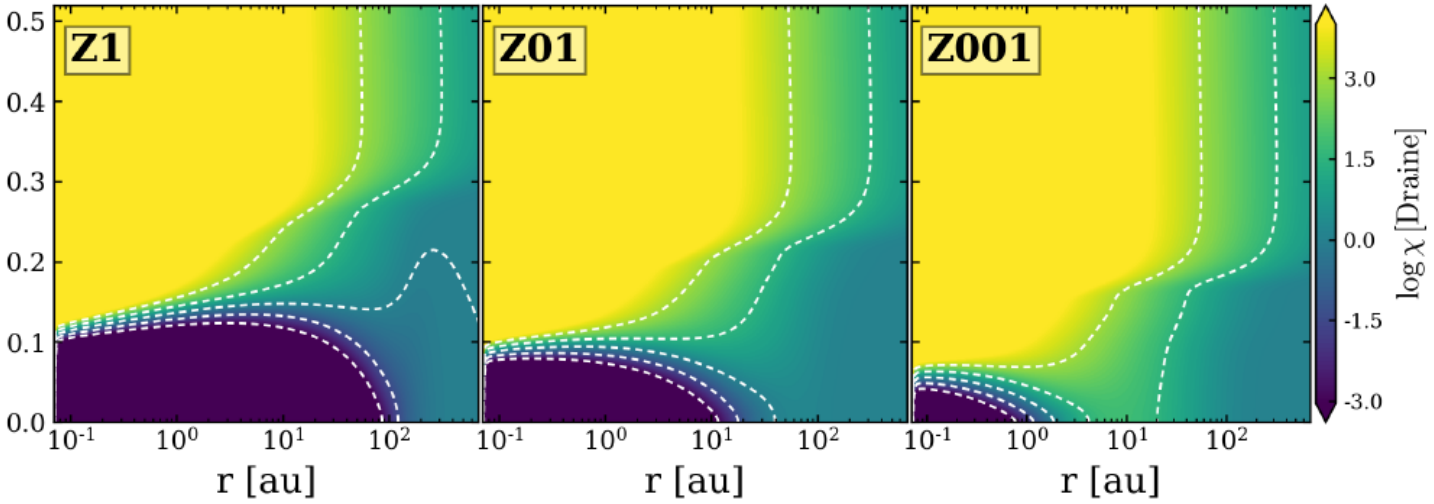
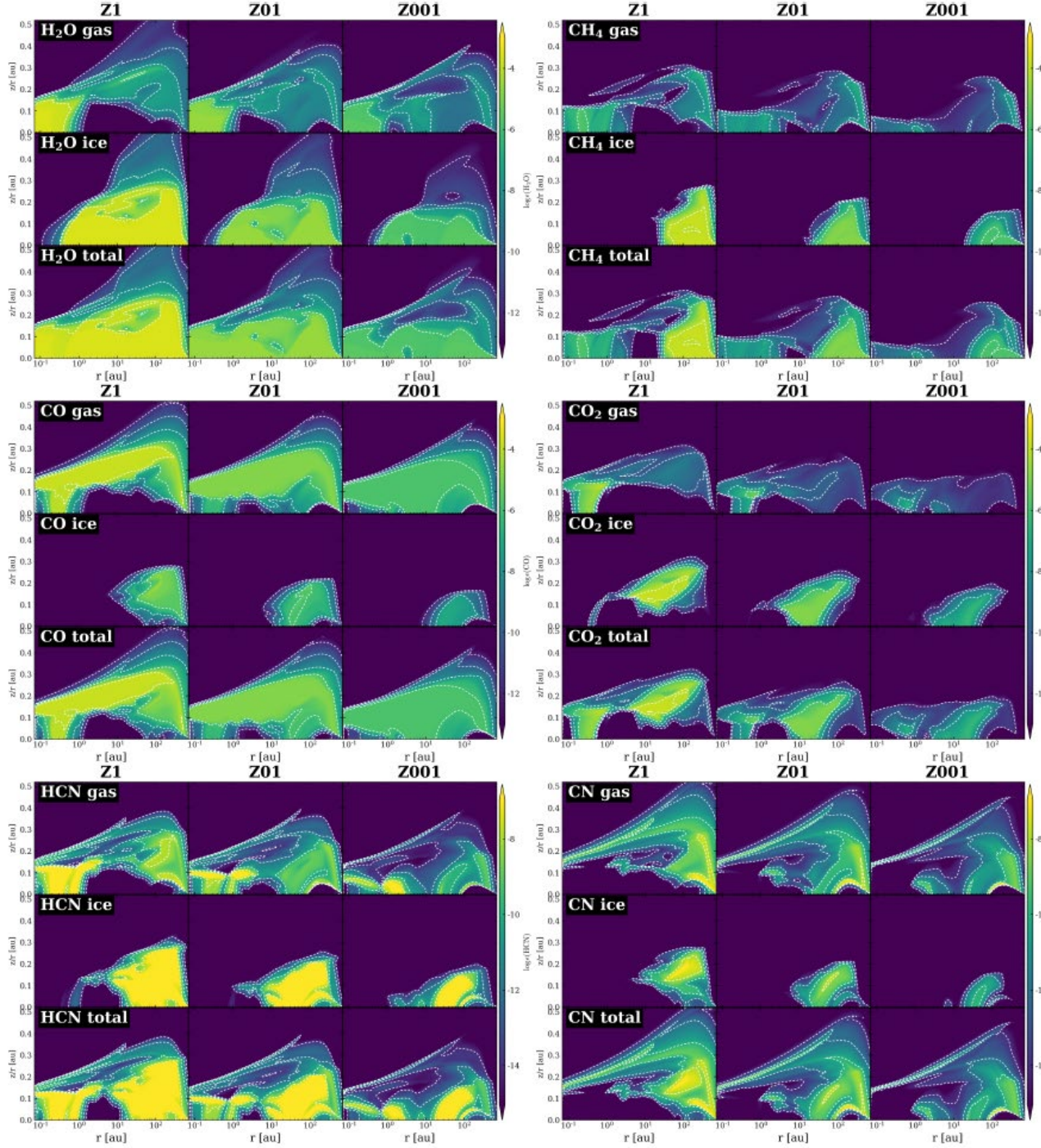


Fig. 6: UV radiation field for the Z1 model (left panel), model Z01 (middle panel), and Z001 (right panel), in units of the Draine field. The dashed contour lines correspond to the tick values in the color bar. The decreasing metallicity enables the UV radiation to get to the midplane at a smaller radius.

化学組成の分布

- **ガス相・固体相** (H2O, CH4, CO, CO2, HCN, CN)
  - 大雑把な傾向
    - 金属量が減少するにつれ、赤道付近にあるガス相分子の空隙は埋められる。
      → UV輻射が増加するので、固体から分子が脱離
    - 赤道付近にある分子組成(total)の空隙は、金属量の減少とともに埋まる
      (例外：H2O)



分子の総数

$$n_{tot} = 2\pi \int_{R_{in}}^{R_{out}} N_{sp} r \, dr$$

$$N_{sp}(r) = \int_0^{z_{max}(r)} n_{sp}(r,z)\, dz$$

$$\mathcal{R} = n_{tot} / n_{tot(sd)}$$

Z=1をスケールしたntotで割る

- **分子の量は単純にZ=1を金属量に従ってスケールした値とは大きく異なる。**
  - ガス温度や輻射場が増加し、分子の量が金属量に対して非線形に変わる。
  - 大雑把には、ガス相にある分子の量は減少すると増える。(例外：CO2)
  - 大雑把には、固体相にある分子の量は減少する。(Z01とZ001の間ではすべてで成り立つ。Z1と比較すると例外たくさん)
- **質量推定に使われるCOは金属量にスケールさせると大幅にCO量を過少評価する**
  - 分子の量にすると、COの金属量依存性は弱い

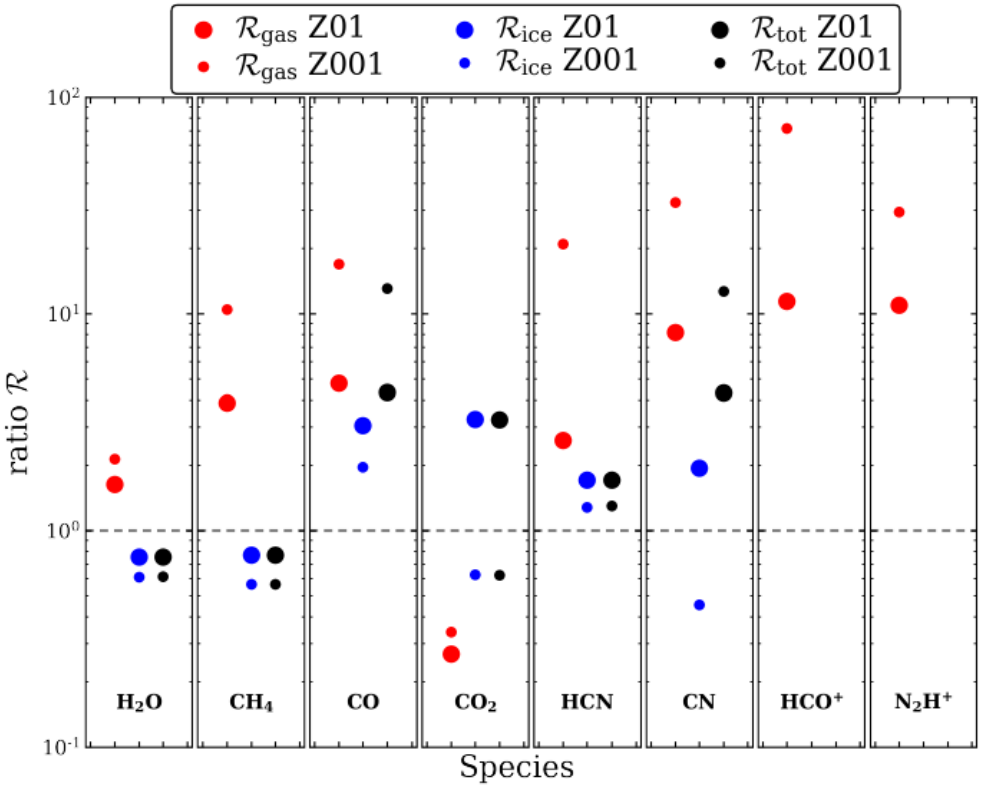


Fig. 13: Ratio $\mathcal{R}$ (see Eq. 7) of the total molecular amount of the scaled-down Z1 and the low metallicity models Z01 and Z001 for each species. The red, blue, and black circles correspond to the ratios of the gaseous, ice, and total (gas + ice) species respectively. The dashed horizontal line shows the value for the ratio equal to 1.

雪線

- **雪線の定義**
  - 赤道面で、
    固相にある分子が気相にある分子と
    一致する場所
- **雪線の金属量依存性**
  - ガス温度が上昇し，UVが増加するので、
    大雑把には雪線は外側に移動する。
  - 固相のリングができる (CO, CN)
    - CNはリングが細くなる
  - H2O雪線はあまり金属量によらない。

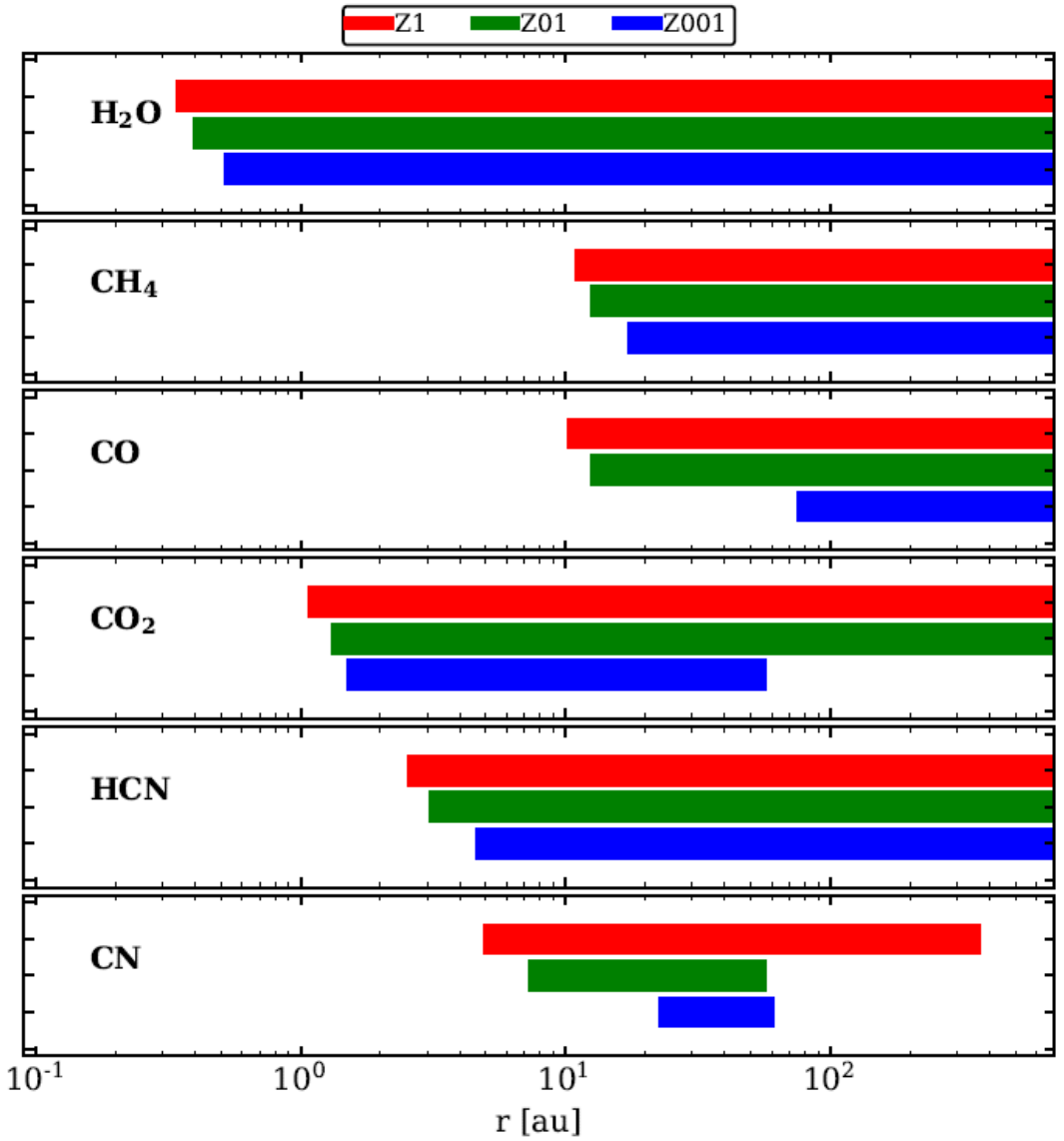


Fig. 15: Snow regions at the midplane for the Z1(red), Z01(green), and Z001(blue) models for all neutral species. The horizontal bars show the region in the midplane where the abundances of the ice species are larger than the abundances of the gaseous species. These regions are enclosed by the inner and outer snowline.

Exponentially amplified magnetic field eliminates disk fragmentation around the Population III protostar

Shingo Hirano, Masahiro N. Machida ★

One critical remaining issue to unclear the initial mass function of the first (Population III) stars is the final fate of secondary protostars formed in the accretion disk, specifically whether they merge or survive. We focus on the magnetic effects on the first star formation under the cosmological magnetic field. We perform a suite of ideal magnetohydrodynamic simulations until 1000 years after the first protostar formation. Instead of the sink particle technique, we employ a stiff equation of state approach to represent the magnetic field structure connecting to protostars. Ten years after the first protostar formation in the cloud initialized with $B_0 = 10^{-20}$ G at $n_0 = 10^4\,\mathrm{cm}^{-3}$, the magnetic field strength around protostars amplifies from pico- to kilo-gauss, which is the same strength as the present-day star. The magnetic field rapidly winds up since the gas in the vicinity of the protostar (≤ 10 au) has undergone several tens orbital rotations in the first decade after protostar formation. As the mass accretion progresses, the vital magnetic field region extends outward, and the magnetic braking eliminates fragmentation of the disk that would form in the unmagnetized model. On the other hand, assuming a gas cloud with small angular momentum, this amplification might not work because the rotation would be slower. However, disk fragmentation would not occur in that case. We conclude that the exponential amplification of the cosmological magnetic field strength, about 10^{-18} G, eliminates disk fragmentation around the Population III protostars.

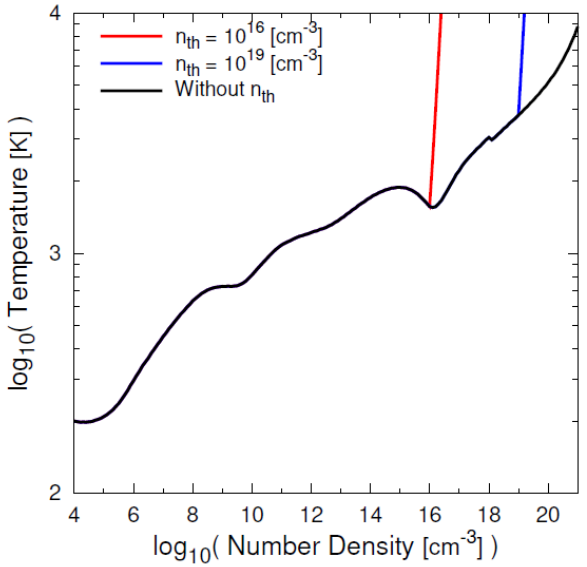
背景

- Pop. III stars → 金属量が0の宇宙最初期にできる星
  - 銀河より先にできて、UVや金属汚染に効く。
- 磁場の役割が未解明
  - 初期宇宙の磁場は弱い ~ 10^{-18} (Ichiki+2006, 二次摂動理論)
  - ガス雲の重力崩壊による増幅は十分磁場増幅しない $B \propto n^{\frac{2}{3}}$
  - 乱流ダイナモ
    - 近年のMHD計算では、重力収縮の間に1桁か2桁しか磁場が乱流ダイナモによって増幅しない。

→この研究では、原始星周囲を回転するガスで磁場をギリギリ捩じることで増幅できないか調べる。

※Hirano+(2021)では、水素原子のみの場合(水素分子が何らかの原因でない)に、原始星の周りの回転による磁場増幅を調べている。今回は水素分子冷却がある場合の研究

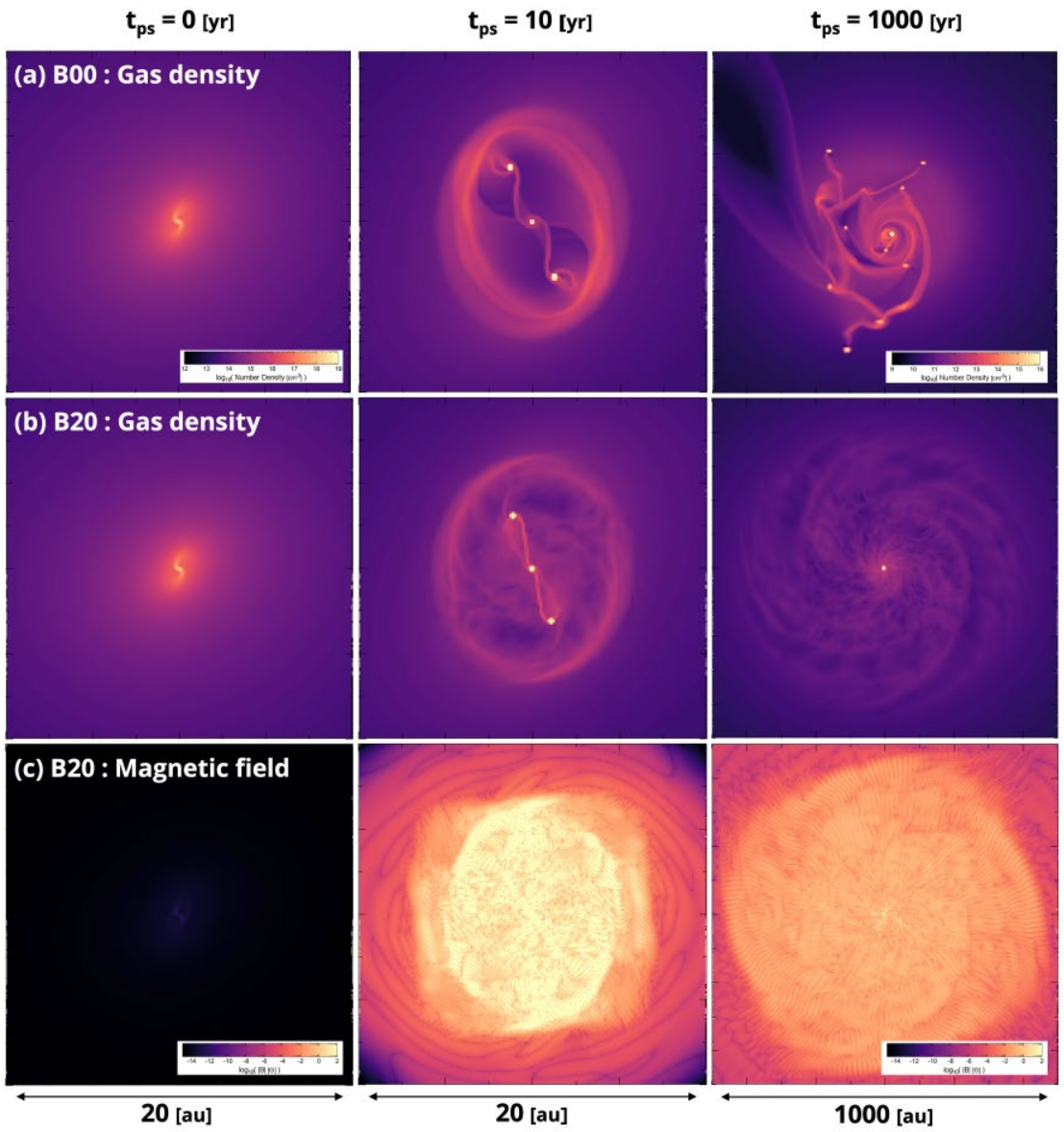
設定



- 熱進化
  - Barotropic EOS, Z=0のガスの1zone熱化学進化計算から
  - 密度閾値$n_{\rm th}$
    - $n_{\rm th} = 10^{19}\,{\rm cm}^{-3}$: t=100yrまで。Radiusがaccreting primordial protostarになるよう
    - $n_{\rm th} = 10^{16}\,{\rm cm}^{-3}$: t=1000yrまで。
- 初期条件
  - Bonner-Ebert球の密度分布を60%だけ全体的に大きくする
  - $M = 4.83 \times 10^3 M_\odot$, $R = 2.38\,{\rm pc}$, $\Omega = 1.31 \times 10^{-14}\,{\rm s}^{-1}$
  - $\alpha_0 = 0.533$, $\beta_0 = 0.0209$
  - No tubulence
- パラメータ
  - 磁場強度 $B_0 = 0, 10^{-20}, 10^{-15}, 10^{-10}\,{\rm G}$ (B00, B20, B15, B10)

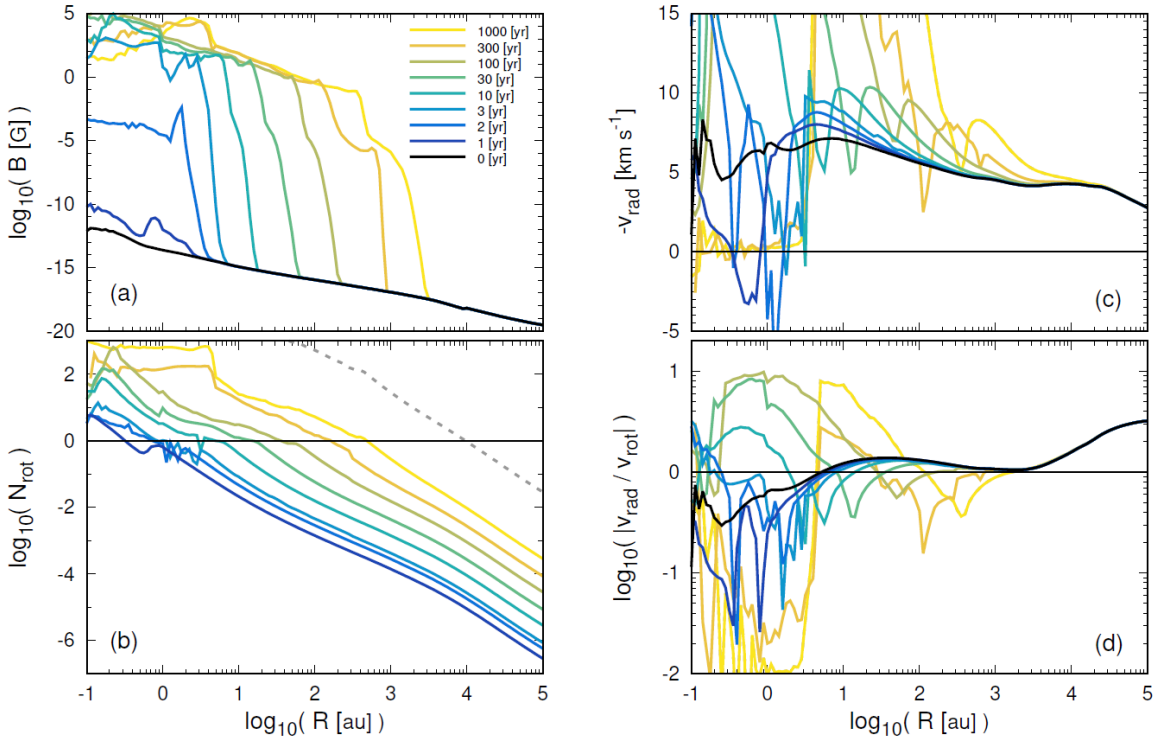
- t=10 yr (t=0は原始星形成時間)
  - 磁場は原始星表面で$\mathbf{kG}$まで増幅
    - $10^{-12}\ \mathrm{G} \rightarrow 10^{3}\ \mathrm{G}$
  - R<10auの領域で磁場が増幅
- t=1000yr
  - 磁場が増幅している領域が500auまで広がる
  - B00では複数の原始星が形成されるが、
    磁場入りモデルではできない。
  - 大局的な渦巻構造で形成
    - 磁気制動により降着

赤道面の断面



- **回転による磁場の増幅**
  - Nrot: 原始星ができてからの回転数。
  - R<10 auの領域は3yr程度で数回回転
  - 磁場が増幅している領域は、Nrot≧1になる領域
- **増幅のメカニズム**
  1. Prototarの回転により周囲の磁場が増幅。
  2. 増幅率は誘導方程式で決まる
  3. Rotation-dominated regionは徐々に外に広がり，そこで1が効く。

→ ただ回転によるダイナモは、poloidal磁場を捩じってtoroidalを作るだけではだめで、poloidal磁場も増幅しないと指数増幅しないが…。
重力収縮でB_rができて、うまい具合になっているのか？



Universal Properties of Dense Clumps in Magnetized Molecular Clouds Formed through Shock Compression of Two-phase Atomic Gases

Kazunari Iwasaki, Kengo Tomida ★ We investigate the formation of molecular clouds from atomic gas by using three-dimensional magnetohydrodynamical simulations,including non-equilibrium chemical reactions, heating/cooling processes, and self-gravity by changing the collision speed V_0 and the angle θ between the magnetic field and colliding flow. We found that the efficiency of the dense gas formation depends on θ. For small θ, anisotropic super-Alfvénic turbulence delays the formation of gravitationally unstable clumps. An increase in θ develops shock-amplified magnetic fields along which the gas is accumulated, making prominent filamentary structures. We further investigate the statistical properties of dense clumps identified with different density thresholds. The statistical properties of the dense clumps with lower densities depend on V_0 and θ because their properties are inherited from the global turbulence structure of the molecular clouds. By contrast, denser clumps appear to have asymptotic universal statistical properties, which do not depend on the properties of the colliding flow significantly. The internal velocity dispersions approach subsonic and plasma β becomes order of unity. We develop an analytic formula of the virial parameter which reproduces the simulation results reasonably well. This property may be one of the reasons for the universality of the initial mass function of stars.

- 原子ガスの磁場に対する集積方向θを変えて分子雲形成を調査
- 磁場にほぼ沿って原子ガスを圧縮すると乱流が卓越した分子雲
- 磁場に傾けて圧縮すると磁場が卓越した分子雲
- 高密度コアの統計的性質は、高密度になるに従い、母体の分子雲の物理的性質に影響しなくなる。

Inferring the Gas-to-Dust Ratio in the Main Planet-Forming Region of Disks

Adam S. Jermyn, Mihkel Kama ★ Measuring the amount of gas and dust in protoplanetary disks is a key challenge in planet formation studies. Here we provide a new set of dust depletion factors and relative mass surface densities of gas and dust for the innermost regions of a sample of protoplanetary disks. We do this by combining stellar theory with observed refractory element abundances in both disk hosts and open cluster stars. Our results are independent of, and complementary to, those obtained from spatially resolved disk observations.

- 背景
  - Dust surface densityは，dust連続波で測定される（optically thinな外側）
  - Gas surface densityは，HDや12COをつかう。
    - Isotope ratioや化学反応ネットワーク，固体への吸着などによる。
  - M>1.4Msunの若い星は，遅い内部攪拌と大きな降着率により，
    光球の組成は 降着した円盤ガスのもので決まる。
    - → 降着が起こるinner diskのgas-to-dust ratioがわかるのでは？

方法

- 星が，non-accreting field starのものと同程度の鉄abundanceで作られたと仮定。$X_{\mathrm{Fe,bulk}}$。光球のガスの割合faccが降着流からきているとして、降着流の鉄abundanceを$X_{\mathrm{Fe,acc}}$とする。
  観測される光球の鉄abundanceは,
  (CAMstars formalism(Jermyn & Kama 2018)を使って計算。Photosphereとbulk of starのmixingを考慮)

$$X_{\mathrm{Fe,obs}} = f_{\mathrm{acc}} X_{\mathrm{Fe,acc}} + (1 - f_{\mathrm{acc}}) X_{\mathrm{Fe,bulk}}$$

- 降着流は星周円盤から生まれ、円盤は星と同じ組成をしているとする。
- 不揮発性の鉄は降着流に固定されているので、$X_{\mathrm{Fe,obs}}$と$X_{\mathrm{Fe,bulk}}$の違いは、gas-to-dust比の変化を表す。

$$\delta \equiv \frac{X_{\mathrm{Fe,acc}}}{X_{\mathrm{Fe,bulk}}}. \qquad \Delta_{\mathrm{g/d}} = 100 \times \delta^{-1},$$

Gas-to-dust

- Fe, Mg, Si, Ca, Sc, Tiに対して
  - Bayesian Multinest sampling algorithmを使って$\log \delta$の事後確率分布を求める。

結果

- Dust-enriched inner diskは，いわゆるGroup IIやfull dust disksと呼ばれ、pebbleがinner diskにdriftしたと予想
- Dust-depleted inner disksは、transitional categoryに属し，dust ringとinner cavityが存在。

Table 1. Summary statistics for the inferred dust enhancement factor δ and photospheric accretion fraction $f_{\rm acc}$ are shown for the stars in our accreting sample. Values for each are given as median, -1σ, and $+1\sigma$. We additionally report the gas-to-dust ratio using the median $\log\delta$, calculated as $\Delta_{\rm g/d} = 100 \times \delta^{-1}$.

Star	$\Delta_{\rm g/d}$	$\log\delta$	-1σ	$+1\sigma$	$\log f_{\rm acc}$	-1σ	$+1\sigma$
Dust-depleted innermost disk							
HD169142	5129	-1.71	-2.62	-0.72	-0.35	-0.46	-0.25
HD141569	4673	-1.67	-2.56	-0.75	-0.47	-0.79	-0.31
T Ori	2890	-1.46	-2.51	-0.50	-0.41	-0.57	-0.27
HD144432	1443	-1.16	-2.41	-0.24	-0.61	-0.84	-0.41
HD142666	987	-0.99	-2.33	-0.25	-0.41	-0.55	-0.23
HD100546	301	-0.48	-0.56	-0.41	-0.01	-0.01	-0.00
HD68695	210	-0.32	-0.40	-0.25	-0.01	-0.01	-0.00
HD245185	194	-0.29	-0.37	-0.20	-0.01	-0.01	-0.00
HD 278937	194	-0.29	-0.35	-0.22	-0.01	-0.01	-0.00
HD101412	182	-0.26	-0.34	-0.18	-0.01	-0.01	-0.00
HD139614	169	-0.23	-0.30	-0.16	-0.01	-0.01	-0.00
HD179218	161	-0.21	-0.28	-0.13	-0.01	-0.01	-0.00
Dust-enriched innermost disk							
HD36112	97	0.01	-0.06	0.08	-0.01	-0.01	-0.00
HD244604	86	0.06	-1.70	0.49	-0.92	-1.32	-0.49
HD31648	84	0.07	0.01	0.14	-0.01	-0.01	-0.00
HD163296	81	0.09	-0.28	0.28	-0.52	-0.79	-0.25

Synthetic ngVLA line observations of a massive star-forming cloud

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Study of pre-stellar cloud evolution requires observations with high sensitivity and resolution, and regions of high-mass star formation are particularly challenging. We wish to quantify, to what accuracy the physical conditions within a massive star-forming cloud can be determined from observations. We are particularly interested in the possibilities offered by the Next Generation VLA (ngVLA) interferometer. We use data from a magnetohydrodynamic simulation of star-formation and concentrate on a filamentary structure that has physical properties similar to an infrared-dark cloud. We produce synthetic ngVLA observations of spectral lines and analyse the column density, gas temperature, and kinematics. The results are compared to ideal observations and the actual 3D model. For a distance of 4 kpc, ngVLA provides a resolution of 0.01 pc even in its most compact configuration. For abundant molecules, such as HCO+, NH3, N2H+, and CO isotopomers, cloud kinematics and structure can be mapped down to sub-arcsec scales. For NH3, a reliable column density map could be obtained for the entire 15 * 40 arcsec cloud, even without additional single-dish data, and kinetic temperatures are recovered to a precision of 1 K. At higher frequencies, the loss of large-scale emission is noticeable. The line observations accurately trace the cloud kinematics, except for the largest scales. The line-of-sight confusion complicates the interpretation of the kinematics, and limits the usefulness of collapse indicators based on the blue asymmetry of optically thick lines. The ngVLA will provide accurate data on the small-scale structure and the physical and chemical state of clouds, even in high-mass star-forming regions at kiloparsec distances. Complementary single-dish data are still essential for estimates of the total column density and the large-scale kinematics.

ngVLAを想定した疑似観測 at 4kpc

- HCO+, NH+, N2H+, COは、数時間の観測でsub-arcsecでマップできる
- Higher frequencyでは、大スケール放射の欠損が効いてくる。単一鏡のデータが必要
- 視線方向の重なりの効果で、観測から得られる速度構造と３次元速度構造は異なり、特に光学的に厚い輝線のblue asymmetryは有効な重力崩壊の指標でない可能性

The eclipse of the V773 Tau B circumbinary disk

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★ A deep (70%) and extended (150 days) eclipse was seen towards the young multiple stellar system V773 Tau in 2010. We interpret it as due to the passage of a circumbinary disk around the B components moving in front of the A components. Our aim is to characterise the orientation and structure of the disk, to refine the orbits of the subcomponents, and to predict when the next eclipse will occur. We combine the photometry from several ground based surveys, construct a model for the light curve of the eclipse, and use high angular resolution imaging to refine the orbits of the three components of the system, A, B and C. Frequency analysis of the light curves, including from the TESS satellite, enables characterisation of the rotational periods of the Aa and Ab stars. A toy model of the circumbinary disk shows that it extends out to approximately 5 au around the B binary and has an inclination of 73 degrees with respect to the orbital plane of AB, where the lower bound of the radius of the disk is constrained by the geometry of the AB orbit and the upper bound is set by the stability of the disk. We identify several frequencies in the photometric data that we attribute to rotational modulation of the Aa and Ab stellar companions. We produce the first determination of the orbit of the more distant C component around the AB system and limit its inclination to 93 degrees. The high inclination and large diameter of the disk, together with the match from theory suggest that B is an almost equal mass, moderately eccentric binary. We identify the rotational periods of the Aa and Ab stars, identify a third frequency in the light curve that we attribute to the orbital period of the stars in the B binary. We predict that the next eclipse will be around 2037, during which both detailed photometric and spectroscopic monitoring will characterise the disk in greater detail.

- 150日にも及ぶ70%のeclipsが多重星系V773 Tau(連星同士が連星を組んでる)で観測され、Bの周連星円盤が示唆される