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研究課題名（和文）Using ALMA to understand the origin of dust polarization in the Beta Pic debris disk

研究課題名（英文）Using ALMA to understand the origin of dust polarization in the Beta Pic debris disk

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研究成果の概要（和文）：デブリ円盤βPicのALMAによるダスト熱放射偏波観測の成果を2022年に発表した。空間分解した画像上では偏波は検出されず、円盤全体で平均すると3σレベルの偏波が見つかった。偏波率は0.51%に相当する。偏波の位置角は円盤の短軸方向に沿っており、これは放射トルクがトロイダル磁場（B-RAT）または放射場の異方性（k-RAT）に対して働くことによるダスト整列モデルの予測と合う。また空間的に平均した偏波の測定から、主に南西3分の1の領域から偏波が生じていることが分かった。k-RATとB-RATを仮定した模擬観測画像から、k-RATがβPicの偏波の主要メカニズムとして有力であることが分かった。

研究成果の学術的意義や社会的意義
A debris disk is very much like the Kuiper Belt in our own (very old, advanced) solar system. Understanding the behavior of material in a debris disk like Beta Pic therefore helps us understand our own Solar System better.

研究成果の概要（英文）：Our ALMA polarization observations of thermal dust emission from the iconic, edge-on debris disk β Pic were published in 2022. While the spatially resolved map does not exhibit detectable polarized dust emission, we detect polarization at the 3-sigma level when averaging the emission across the entire disk. The corresponding polarization fraction is 0.51%. The polarization position angle is aligned with the minor axis of the disk, as expected from models of dust grains aligned via radiative alignment torques (RAT) with respect to a toroidal magnetic field (B-RAT) or with respect to the anisotropy in the radiation field (k-RAT). When averaging the polarized emission across the outer versus inner thirds of the disk, we find that the polarization arises primarily from the SW third. We perform synthetic observations assuming grain alignment via both k-RAT and B-RAT. We find that k-RAT is the likely mechanism producing the polarized emission in β Pic.

研究分野：Astronomy

キーワード：Star formation　Radio astronomy　Polarization　Dust　Debris disks　Magnetic fields　Scattering

様　式　C－１９、F－１９－１、Z－１９（共通）

１．研究開始当初の背景

Because of its extremely high brightness, low optical depth, and edge-on orientation, β Pic offers a unique laboratory to test different dust-grain alignment mechanisms. At the low densities and optical depths associated with the diffuse interstellar medium and the protostellar cores/envelopes surrounding embedded Class 0 protostars, dust grains are expected to be aligned by the magnetic field via the radiative torque mechanism (“*B*-RATs”; Lazarian & Hoang 2007, *MNRAS*, 378, 910). Thus, for decades dust polarization has been used as a proxy for the magnetic field in star-forming material at scales of several kpc down to a few × 100 au. However, over the last few years, many theoretical and observational studies have found that at high enough densities and optical depths (e.g., in a protoplanetary disk), polarization observations at submillimeter wavelengths can be explained by models of dust scattering (e.g., Kataoka et al. 2015, *ApJ*, 809, 78; Yang et al. 2016, *MNRAS*, 456, 2794). In addition, Tazaki et al. (2017, *ApJ*, 839, 56) recently described how, under certain circumstances, dust grains can be aligned via radiative torques not with respect to the magnetic field, but with respect to the dust emission gradient (“radiative alignment,” or “*k*-RATs”). This effect was seen shortly thereafter in 3 mm polarization observations of HL Tau by Kataoka et al. (2017, *ApJL*, 844, 5); this effect remains poorly understood, however, as detailed models of the radiative-alignment mechanism do not fit the 3 mm HL Tau data in detail (Yang et al. 2019, *MNRAS*, 483, 2371).

Magnetic field strengths in debris disks are observationally unconstrained. In the first work in the new field of gas-transport in debris disks, Kral et al. (2016, *MNRAS*, 461, 845) found that the gas-mass transport observed in β Pic could be enabled by enhanced viscosity from the magnetorotational instability (MRI; Balbus & Hawley 1991, *ApJ*, 376, 214). A follow-up study by Kral & Latter (2016, *MNRAS*, 461, 1614) confirmed that indeed, the MRI can develop in debris disk environments and may even be more active than in protoplanetary disks because of the higher ionization fraction of debris-disk gas. However, a peculiarity of the MRI in debris disks is that it can turn off in the presence of a relatively weak magnetic field of just a few μG—a strength similar to that of the 1–10 μG interplanetary magnetic field in our Solar System (Burlaga & Ness 2012, *ApJ*, 744, 51), and also similar to the 6 μG field strength in the interstellar medium (Heiles & Troland 2005, *ApJ*, 624, 773).

２．研究の目的

Our main purpose was to characterize the magnetic field in a debris disk. This is essential for answering our key scientific question, which is, What drives the evolution of these gaseous Solar-System precursors around main-sequence stars? However, we must consider different grain-alignment mechanisms, as grains can be aligned not only by the magnetic field, but by other processes as well. We consider two mechanisms (magnetic and radiative alignment) below.

If magnetic alignment of dust grains via *B*-RATs is the dominant polarization-producing mechanism in a debris disk like β Pic, we would be able to put a limit on the field strength, since a “critical field strength”—i.e., the minimum magnetic field strength necessary to align grains—can be derived by comparing the magnetic alignment vs. collisional dealignment timescales. Following Equation 1 in §4.3.1 of Hughes et al. (2009, *ApJ*, 704, 1204), we use the known values of the temperature and gas density in β Pic ($T_{\rm dust}$ = 85 K; $T_{\rm gas}$ = 30 K; n ~ 250 cm^{-3}; Dent et al. 2014; Kral et al. 2016) and find a critical field strength for 1 mm-sized grains of ≲ 1μG. The low-density conditions of debris disks are very similar to those of molecular clouds, where magnetic grain-alignment is well established. It is thus clear that debris disks are the ideal circumstellar environments to search for magnetically aligned dust grains. Furthermore, based on this estimate, a detection of magnetically aligned grains in β Pic would imply that the magnetic field may indeed be strong enough to suppress the MRI. This would require testing whether the MRI is actually at work in these disks and might require us to consider new mechanisms that could produce the viscosity necessary for gas transport in debris disks.

However, radiative alignment could also be the dominant alignment mechanism in debris disks, aligning the grains observed in β Pic with respect to the gradient in the radiation field. The extremely low gas density in β Pic means that collisional dealignment will be minimal, enabling both magnetic and radiative alignment; however, the relative timescales of magnetic vs. radiative alignment are not well constrained (Tazaki et al. 2017).

３．研究の方法

We used standard observations of polarized thermal dust emission from the ALMA observatory to investigate the alignment mechanisms of dust grains in β Pic. Our approved ALMA observations allowed us to map the polarization in the source, which we did with standard data reduction and image processing techniques.

４．研究成果

Our results, published in Hull et al. 2022, feature 870 μm ALMA polarization observations of thermal dust emission from the iconic, edge-on debris disk β Pic. While the spatially resolved map does not exhibit detectable polarized dust emission, we detect polarization at the ~3σ level when averaging the emission across the entire disk. The corresponding polarization fraction is $P_{frac} = 0.51\% \pm 0.19\%$. The polarization position angle χ is aligned with the minor axis of the disk, as expected from models of dust grains aligned via radiative alignment torques (RAT) with respect to a toroidal magnetic field (B-RAT) or with respect to the anisotropy in the radiation field (k-RAT). When averaging the polarized emission across the outer versus inner thirds of the disk, we find that the polarization arises primarily from the SW third. We perform synthetic observations assuming grain alignment via both k-RAT and B-RAT. Both models produce polarization fractions close to our observed value when the emission is averaged across the entire disk. When we average the models in the inner versus outer thirds of the disk, we find that k-RAT is the likely mechanism producing the polarized emission in β Pic. A comparison of timescales relevant to grain alignment also yields the same conclusion. For dust grains with realistic aspect ratios (i.e., $s > 1.1$), our models imply low grain-alignment efficiencies.

5．主な発表論文等

〔雑誌論文〕　計5件（うち査読付論文　5件／うち国際共著　5件／うちオープンアクセス　3件）

1．著者名 Teague, Richard; Hull, Charles L. H.; Guilloteau, Stephane; Bergin, Edwin A.; Dutrey, Anne; Henning, Thomas; Kuiper, Rolf; Semenov, Dmitry; Stephens, Ian W.; Vlemmings, Wouter H. T.	4．巻 922
2．論文標題 Discovery of Molecular-line Polarization in the Disk of TW Hya	5．発行年 2021年
3．雑誌名 The Astrophysical Journal	6．最初と最後の頁 139
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/ac2503	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Hull, Charles L. H. ; Yang, Haifeng ; Cortes, Paulo C. ; Dent, William R. F. ; Kral, Quentin ; Li, Zhi-Yun ; Le Gouellec, Valentin J. M. ; Hughes, A. Meredith ; Milli, Julien ; Teague, Richard ; Wyatt, Mark C.	4．巻 930
2．論文標題 Polarization from Aligned Dust Grains in the β Pic Debris Disk	5．発行年 2022年
3．雑誌名 The Astrophysical Journal	6．最初と最後の頁 49
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/ac6023	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Lin, Zhe-Yu Daniel; Li, Zhi-Yun; Yang, Haifeng; Looney, Leslie; Stephens, Ian; Hull, Charles L. H.	4．巻 496
2．論文標題 Validating scattering-induced (sub)millimetre disc polarization through the spectral index, wavelength-dependent polarization pattern, and polarization spectrum: the case of HD 163296	5．発行年 2020年
3．雑誌名 Monthly Notices of the Royal Astronomical Society	6．最初と最後の頁 169-181
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/mnras/staa1499	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Ohashi, Satoshi; Kataoka, Akimasa; van der Marel, Nienke; Hull, Charles L. H.; Dent, William R. F.; Pohl, Adriana; Pinilla, Paola; van Dishoeck, Ewine F.; Henning, Thomas	4．巻 900
2．論文標題 Solving Grain Size Inconsistency between ALMA Polarization and VLA Continuum in the Ophiuchus IRS 48 Protoplanetary Disk	5．発行年 2020年
3．雑誌名 The Astrophysical Journal	6．最初と最後の頁 81
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/abaab4	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Hull, Charles L. H.; Cortes, Paulo C.; Gouellec, Valentin J. M. Le; Girart, Josep M.; Nagai, Hiroshi; Nakanishi, Kouichiro; Kameno, Seiji; Fomalont, Edward B.; Brogan, Crystal L.; Moellenbrock, George A.; Paladino, Rosita; Villard, Eric	4．巻 132
2．論文標題 Characterizing the Accuracy of ALMA Linear-polarization Mosaics	5．発行年 2020年
3．雑誌名 Publications of the Astronomical Society of the Pacific	6．最初と最後の頁 1015
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1538-3873/ab99cd	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

〔学会発表〕　計5件（うち招待講演　3件／うち国際学会　1件）

1．発表者名 Charles L. H. Hull
2．発表標題 The Explosion in Orion-KL as Seen by Mosaicking the Magnetic Field with ALMA
3．学会等名 SOFIA B-fields and filaments meeting (contributed talk, virtual)
4．発表年 2021年

1．発表者名 Charles L. H. Hull
2．発表標題 Star formation, polarization, and magnetic fields in the ALMA era
3．学会等名 Irish National Astronomy Meeting (invited talk, virtual)（招待講演）（国際学会）
4．発表年 2021年

1．発表者名 Charles L. H. Hull
2．発表標題 Star formation, polarization, and magnetic fields in the ALMA era
3．学会等名 NRAO (invited talk, virtual)（招待講演）
4．発表年 2021年

１．発表者名 C. Hull
２．発表標題 Non-detection of spectral-line polarization in the TW Hya protoplanetary disk
３．学会等名 The magnetic field awakens (remote; Dec 2020)
４．発表年 2020年

１．発表者名 C. Hull
２．発表標題 Star formation, polarization, and magnetic fields in the ALMA era
３．学会等名 Rice University, colloquium (remote: Feb 2021)（招待講演）
４．発表年 2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

C. Hull's publication list https://ui.adsabs.harvard.edu/public-libraries/kqeLWrvzQl-ZD7YGSqFa7A NAOJ main website https://www.nao.ac.jp/en/ ALMA Observatory website https://www.almaobservatory.org/en/

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関