様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　５ 年　 ６ 月 ２５ 日現在

機関番号：６２６１６

研究種目：若手研究

研究期間：2018～2022

課題番号：１８Ｋ１３５８６

研究課題名（和文）Using magnetic fields to probe the core-fragmentation model of binary formation

研究課題名（英文）Using magnetic fields to probe the core-fragmentation model of binary formation

研究代表者

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交付決定額（研究期間全体）：（直接経費）　　3,200,000円

研究成果の概要（和文）：Hull et al. 2020で本課題の結果を報告した。ALMAを用いて原始連星系（BHR 71 IRS1、IRS2）の1.3 mmダスト放射偏波観測を行った。IRS1は星形成時から付随すると考えられる砂時計型の磁場を持つ。一方、IRS2は双極状アウトフローの影響を受けた磁場を示す。IRS2では、偏波はアウトフロー空洞の壁面に限られ、赤方偏移側のアウトフローの北端部分では、アウトフローと冷たく濃いガスのフィラメントに挟まれた領域にのみ偏波が検出された。このことから、IRS2が強い偏波を示すのは、アウトフロー壁面が照射されることによって、磁場に対しダストが整列するためであると示唆される。

研究成果の学術的意義や社会的意義
Studying the formation of stars gives us a view into where we, as human beings, came from, because by studying how stars form, we are studying the environments in which solar systems like our own form. Studying binary stars is important since half of the stars in the Milky Way are binaries.

研究成果の概要（英文）：The results of this study were published in Hull et al. 2020a (ApJ, 892, 152). In that work, we presented 1.3 mm ALMA observations of polarized dust emission toward the wide-binary protostellar system BHR 71 IRS1 and IRS2. IRS1 features what appears to be a natal, hourglass-shaped magnetic field. In contrast, IRS2 exhibits a magnetic field that has been affected by its bipolar outflow. Toward IRS2, the polarization is confined mainly to the outflow cavity walls. Along the northern edge of the redshifted outflow cavity of IRS2, the polarized emission is sandwiched between the outflow and a filament of cold, dense gas traced by N2D+, toward which no dust polarization is detected. This suggests that the origin of the enhanced polarization in IRS2 is the irradiation of the outflow cavity walls, which enables the alignment of dust grains with respect to the magnetic field -- but only to a depth of approximately 300 au, beyond which the dust is cold and unpolarized.

研究分野：Astronomy

キーワード：Star formation　Radio astronomy　Binary stars　Protostars　Polarization　Magnetic fields　Dust

１．研究開始当初の背景

Early theories of magnetized star-formation suggested that at small scales (~1000 au), the formation of individual (or binary) protostars should be regulated by a strong magnetic field. If observed with high-enough resolution, one should see an “hourglass” morphology in the magnetic field lines, where a strong, poloidal magnetic field is pinched by the gravitational infall very near the central source. And in fact, several examples of hourglass magnetic fields were seen in some of the first sources whose magnetic fields were observed at high resolution, including the bright, deeply embedded Class 0 protostellar sources NGC 1333-IRAS 4A (Girart et al. 2006, *Science,* 313, 812), IRAS 16293 (Rao et al. 2009, *ApJ,* 707, 921), and L1157 (Stephens et al. 2013, *ApJL,* 769, 15, incl. C. Hull). These sources exhibit other characteristics of strong-field star formation, including powerful outflows and high magnetic field strengths of a few milli-Gauss. Furthermore, the sources are not extremely fragmented, either being single sources (L1157), binaries (IRAS 4A), or possibly triple systems (IRAS 16293), consistent with expectations of fragmentation models. This is in contrast to recent ALMA observations that show a large amount of fragmentation in a weakly magnetized region with chaotic magnetic fields (Hull et al. 2017a, *ApJL,* 842, 9). However, after more than a decade of high-resolution observations of magnetic fields in forming stars with BIMA, the SMA, CARMA, and now ALMA, it has become clear that hourglass-shaped fields appear to be relatively rare. Why is it, then, that such a high fraction of the first sources to be observed exhibited hourglass-shaped magnetic fields?

When astronomers used early interferometers to measure magnetic fields via polarized dust emission, they observed sources that were *very bright.* This is because the polarized intensity from thermal dust emission in young, Class 0 protostellar sources is generally only a few percent of the total source intensity. We proposed that this is because strong, poloidal fields in highly magnetized protostars help to funnel infalling material onto the central source more efficiently, thus increasing their brightness. We predicted that one or both components of BHR 71—which is an extremely bright system, and was the target of this study—are also strongly magnetized, and will exhibit an hourglass-shaped magnetic field. Other similarities lead us to this conclusion as well: like IRAS 4A and IRAS 16293, the two components of BHR 71 generate very powerful outflows, which may indicate strong magnetic fields; and like L1157, BHR 71 is embedded in a relatively isolated Bok globule, where the magnetic field is less likely to be perturbed by external sources.

Note that IRAS 4A and IRAS 16293 have extremely well ordered, hourglass fields in spite of having extremely powerful outflows that are *not* aligned with the hourglass axis, suggesting that the outflows have not yet had time to disrupt the field structure. This is in contrast with recent observations of several sources in Serpens, one of which has chaotic magnetic fields (Hull et al. 2017a) and another of which exhibits a magnetic field that has clearly been shaped by the outflow (Hull et al. 2017b, *ApJ,* 847, 92). Considering the youth of BHR 71, we predicted that the outflows from the two sources will not have had time to disturb the magnetic field, allowing us to see the morphology of the magnetic field during the earliest stages of the fragmentation process.

２．研究の目的

The key purpose and main scientific question driving this research program was to determine whether the individual components of this wide binary system have magnetic fields that are aligned with one another, which would suggest that the magnetic field in their common natal envelope played a role in regulating the fragmentation of the binary. Another key purpose was to determine if an hourglass-shaped field is visible around one or both binary components. We predicted that this is likely given the similarity of BHR 71 and other highly magnetized sources, combined with the fact that both IRS1 and IRS2 are viewed nearly edge on (inclination angles >85°, with outflows nearly in the plane of the sky), which makes it easier to detect the hourglass shape (see, e.g., inclination-based modeling by Frau et al. 2011, *AAP,* 535, 44).

３．研究の方法

We used standard observations of polarized thermal dust emission from the ALMA observatory to investigate the predictions we list above.　Our approved ALMA observations allowed us to map the magnetic field morphology of the two components in BHR 71 on the 100–1000 au scale that is crucial to multiple star formation, which we did with standard data reduction and image processing techniques.

４．研究成果

The results of this study were published in Hull et al. 2020 (ApJ, 892, 152).　In that work, we presented 1.3 mm ALMA observations of polarized dust emission toward the wide-binary protostellar system BHR 71 IRS1 and IRS2. IRS1 features what appears to be a natal, hourglass-shaped magnetic field. In contrast, IRS2 exhibits a magnetic field that has been affected by its bipolar outflow. Toward IRS2, the polarization is confined mainly to the outflow cavity walls. Along the northern edge of the redshifted outflow cavity of IRS2, the polarized emission is sandwiched between the outflow and a filament of cold, dense gas traced by N_2D^+, toward which no dust polarization is detected. This suggests that the origin of the enhanced polarization in IRS2 is the irradiation of the outflow cavity walls, which enables the alignment of dust grains with respect to the magnetic field—but only to a depth of ~300 au, beyond which the dust is cold and unpolarized. However, in order to align grains deep enough in the cavity walls, and to produce the high polarization fraction seen in IRS2, the aligning photons are likely to be in the mid- to far-infrared range, which suggests a degree of grain growth beyond what is typically expected in very young, Class 0 sources. Finally, toward IRS1 we see a narrow, linear feature with a high (10%-20%) polarization fraction and a well-ordered magnetic field that is not associated with the bipolar outflow cavity. We speculate that this feature may be a magnetized accretion streamer; however, this has yet to be confirmed by kinematic observations of dense-gas tracers.

５．主な発表論文等

〔雑誌論文〕　計9件（うち査読付論文　9件／うち国際共著　9件／うちオープンアクセス　8件）

１．著者名 Fernandez-Lopez, M., Sanhueza, P., Zapata, L. A., Stephens, I., Hull, C., Zhang, Q., Girart, J. M., Koch, P. M., Cortes, P., Silva, A., Tatematsu, K., Nakamura, F., Guzman, A. E., Nguyen Luong, Q., Guzman Ccolque, E., Tang, Y.-W., Chen, H.-R. V.	４．巻 913
２．論文標題 Magnetic Fields in Massive Star-forming Regions (MagMaR). I. Linear Polarized Imaging of the Ultracompact H II Region G5.89-0.39	５．発行年 2021年
３．雑誌名 The Astrophysical Journal	６．最初と最後の頁 29
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/abf2b6	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 Sanhueza, P., Girart, J. M., Padovani, M., Galli, D., Hull, C. L. H., Zhang, Q., Cortes, P., Stephens, I. W., Fernandez-Lopez, M., Jackson, J. M., Frau, P., Kock, P. M., Wu, B., Zapata, L. A., Olguin, F., Lu, X., Silva, A., Tang, Y.-W., Sakai, T., Guzman, A. E., Tatematsu, K., Nakamura, F., Chen, H.-R. V.	４．巻 915
２．論文標題 Gravity-driven Magnetic Field at 1000 au Scales in High-mass Star Formation	５．発行年 2021年
３．雑誌名 The Astrophysical Journal Letters	６．最初と最後の頁 10
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/2041-8213/ac081c	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 Cortes, Paulo C., Sanhueza, Patricio, Houde, Martin, Martin, Sergio, Hull, Charles L. H., Girart, Josep M., Zhang, Qizhou, Fernandez-Lopez, Manuel, Zapata, Luis A., Stephens, Ian W., Li, Hua-bai, Wu, Benjamin, Olguin, Fernando, Lu, Xing, Guzman, Andres E., Nakamura, Fumitaka	４．巻 923
２．論文標題 Magnetic Fields in Massive Star-forming Regions (MagMaR). II. Tomography through Dust and Molecular Line Polarization in NGC 6334I(N)	５．発行年 2021年
３．雑誌名 The Astrophysical Journal	６．最初と最後の頁 204
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/ac28a1	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.; Le Gouellec, Valentin J. M.; Girart, Josep M.; Tobin, John J.; Bourke, Tyler L.	４．巻 892
２．論文標題 Understanding the Origin of the Magnetic Field Morphology in the Wide-binary Protostellar System BHR 71	５．発行年 2020年
３．雑誌名 Astrophysical Journal	６．最初と最後の頁 152
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/ab5809	査読の有無 有
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１．著者名 Myers, Philip C.; Stephens, Ian W.; Auddy, Sayantan; Basu, Shantanu; Bourke, Tyler L.; Hull, Charles L. H.	４．巻 896
２．論文標題 Magnetic Field Structure in Spheroidal Star-forming Clouds. II. Estimating Field Structure from Observed Maps	５．発行年 2020年
３．雑誌名 Astrophysical Journal	６．最初と最後の頁 163
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/ab9110	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 Le Gouellec, V. J. M.; Maury, A. J.; Guillet, V.; Hull, C. L. H.; Girart, J. M.; Verliat, A.; Mignon-Risse, R.; Valdivia, V.; Hennebelle, P.; Gonzalez, M.; Louvet, F.	４．巻 644
２．論文標題 A statistical analysis of dust polarization properties in ALMA observations of Class 0 protostellar cores	５．発行年 2020年
３．雑誌名 Astronomy & Astrophysics	６．最初と最後の頁 11
掲載論文のDOI（デジタルオブジェクト識別子） 10.1051/0004-6361/202038404	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 Arce-Tord, C.; Louvet, F.; Cortes, P. C.; Motte, F.; Hull, C. L. H.; Le Gouellec, V. J. M.; Garay, G.; Nony, T.; Didelon, P.; Bronfman, L.	４．巻 640
２．論文標題 Outflows, cores, and magnetic field orientations in W43-MM1 as seen by ALMA	５．発行年 2020年
３．雑誌名 Astronomy & Astrophysics	６．最初と最後の頁 111
掲載論文のDOI（デジタルオブジェクト識別子） 10.1051/0004-6361/202038024	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 Le Gouellec, V.J.M., Hull, C.L.H., Maury, A.J., Girart, J.M., Tychoniec, L., Kristensen, L.E., Li, Z.-Y., Louvet, F., Cortes, P.C., and Rao, R.	４．巻 885
２．論文標題 Characterizing magnetic field morphologies in three Serpens protostellar cores with ALMA	５．発行年 2019年
３．雑誌名 Astrophysical Journal	６．最初と最後の頁 1-24
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/ab43c2	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, C.L.H. and Zhang, Q.	４．巻 6, 3
２．論文標題 Interferometric observations of magnetic fields in forming stars	５．発行年 2019年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.3389/fspas.2019.00003	査読の有無 有
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〔学会発表〕　計27件（うち招待講演　17件／うち国際学会　21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)（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 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
Star formation, polarization, and magnetic fields in the ALMA era

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Allegro ARC Node, Leiden, Netherlands (invited talk, virtual)（招待講演）

４．発表年
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Star formation, polarization, and magnetic fields in the ALMA era

３．学会等名
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４．発表年
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Star formation, polarization, and magnetic fields in the ALMA era

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４．発表年
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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
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４．発表年
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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 (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 Magnetized star formation in the ALMA era
３．学会等名 Tinsley Scholar Lecture (University of Texas, Austin, USA; Sep 2019)（招待講演）（国際学会）
４．発表年 2019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 Universidad de Chile colloquium (Santiago, Chile; Jun 2019)（招待講演）（国際学会）
４．発表年 2019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 Pontificia Universidad Catolica de Chile colloquium (Santiago, Chile; Oct 2019)（招待講演）（国際学会）
４．発表年 2019年

１．発表者名
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２．発表標題
Star formation and magnetic fields in the ALMA era

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４．発表年
2019年

１．発表者名
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２．発表標題
Star formation, polarization, and magnetic fields in the ALMA era

３．学会等名
University of Copenhagen STARPLAN seminar (Copenhagen, Denmark; Nov 2019)（招待講演）（国際学会）

４．発表年
2019年

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２．発表標題
Star formation, polarization, and magnetic fields in the ALMA era

３．学会等名
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４．発表年
2019年

１．発表者名
C. Hull

２．発表標題
Understanding the magnetic field in the BHR 71 protostellar binary

３．学会等名
American Astronomical Society annual meeting (Honolulu, Hawaii, USA; Jan 2020)（国際学会）

４．発表年
2020年

１．発表者名
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２．発表標題
Star formation, polarization, and magnetic fields in the ALMA era

３．学会等名
NAOJ ALMA-J seminar (Mitaka, Tokyo, Japan; Jan 2020)

４．発表年
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１．発表者名
V. Le Gouellec

２．発表標題
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３．学会等名
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４．発表年
2019年

１．発表者名
V. Le Gouellec

２．発表標題
Understanding the nature of polarized dust emission in Class 0 protostellar cores with ALMA

３．学会等名
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４．発表年
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１．発表者名
V. Le Gouellec

２．発表標題
Characterizing Magnetic Field Morphologies in Three Serpens Protostellar Cores with ALMA

３．学会等名
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４．発表年
2019年

１．発表者名
C. Hull

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Star formation, polarization, and magnetic fields in the ALMA era

３．学会等名
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４．発表年
2018年

１．発表者名
V. Le Gouellec

２．発表標題
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３．学会等名
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４．発表年
2018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
Colloquium at the Universidad de Valparaiso, Chile (Nov 2018)（招待講演）（国際学会）

４．発表年
2018年

１．発表者名
V. Le Gouellec

２．発表標題
ALMA dust polarized observations from Class 0 protostellar sources in the Serpens star forming region

３．学会等名
Workshop on Polarization in Protoplanetary Disks and Jets, Barcelona, Spain (May 2019)（国際学会）

４．発表年
2019年

１．発表者名
C. Hull

２．発表標題
TBD: 2 talks, 1 on disk polarization, 1 on magnetic fields in star formation

３．学会等名
Tinsley Scholar lectures, UT Austin, USA (Sep 2019)（招待講演）（国際学会）

４．発表年
2019年

１．発表者名
C. Hull

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Star formation and magnetic fields in the ALMA era

３．学会等名
ALMA 2019, Cagliari, Sardinia, Italy (Oct 2019)（招待講演）（国際学会）

４．発表年
2019年

１．発表者名
C. Hull

２．発表標題
Understanding the origin of the magnetic field morphology in the wide-binary protostellar system BHR 71

３．学会等名
American Astronomical Society annual meeting, Honolulu, Hawaii (Jan 2020)（国際学会）

４．発表年
2019年

１．発表者名
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Star formation, polarization, and magnetic fields in the ALMA era

３．学会等名
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４．発表年
2019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