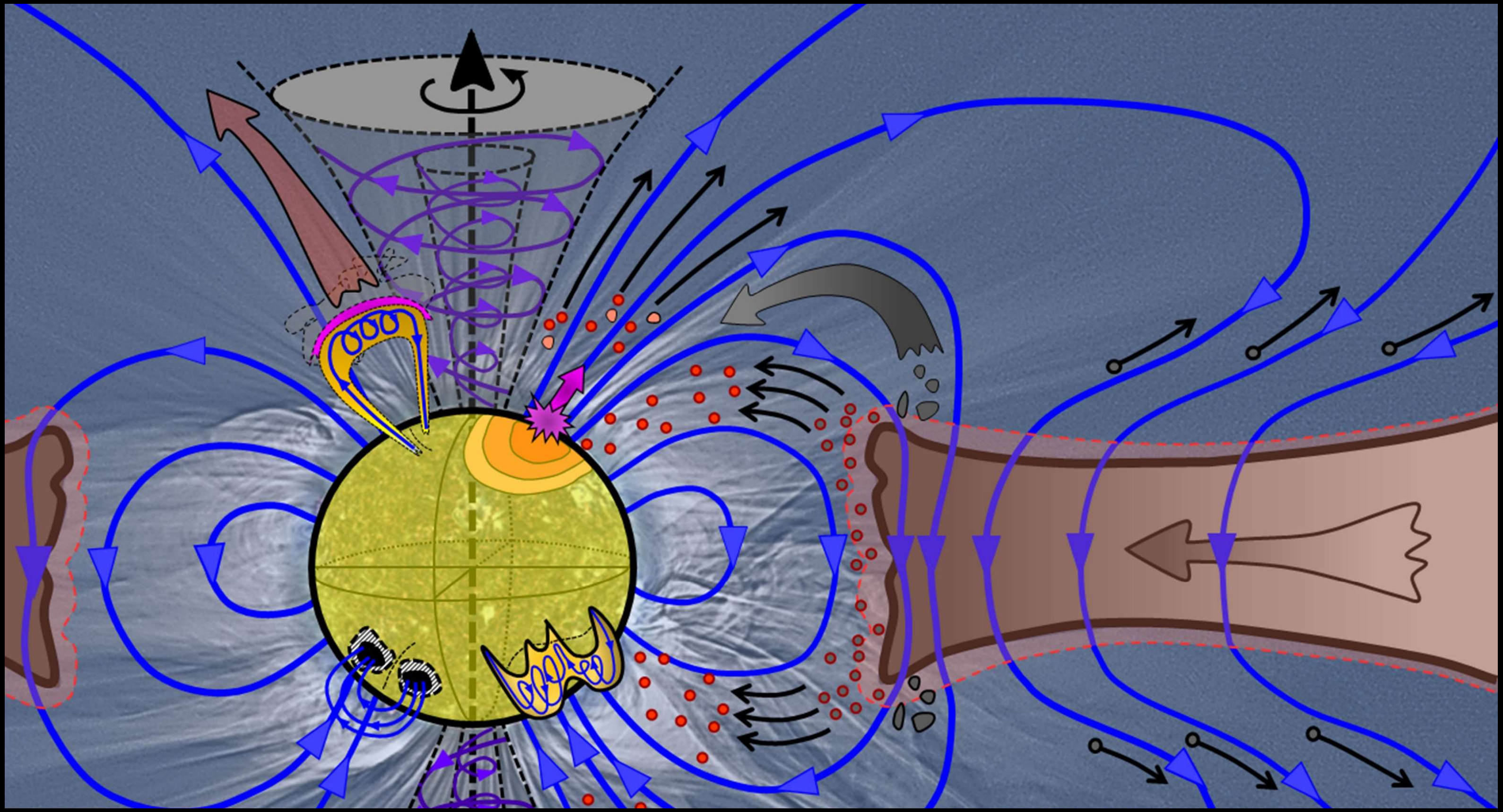
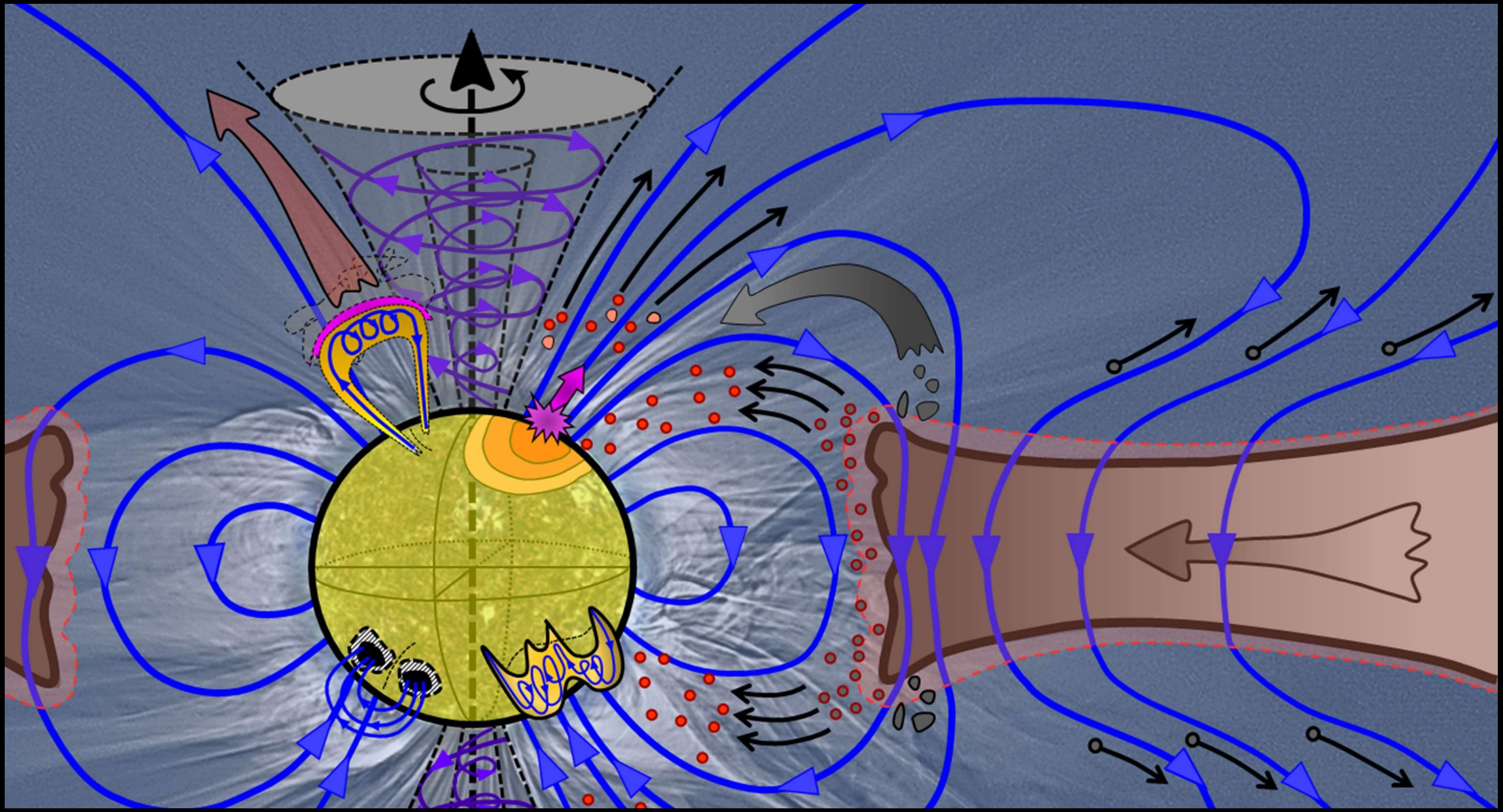


$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{B}) - \vec{\nabla} \times (\eta_{\mathrm{OD}} \cdot \vec{\nabla} \times \vec{B}) + \vec{\nabla} \times \{\eta_{\mathrm{AD}} \cdot (\vec{\nabla} \times \vec{B}) \times \vec{B}\} - \vec{\nabla} \times [\vec{\nabla} \times \{\eta_{\mathrm{HD}} \cdot (\vec{\nabla} \times \vec{B}) \times \vec{B}\}]$$

U. v. Kusserow, Bremen

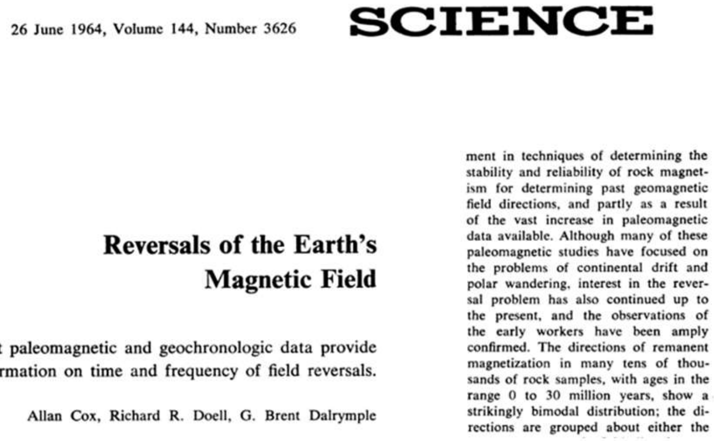
MHD and the Formation of the Magnetic Solar System

A didactically oriented approach



$$\frac{\partial \vec{\boldsymbol{B}}}{\partial t} = \vec{\nabla} \times (\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}}) - \vec{\nabla} \times (\eta_{\mathrm{OD}} \cdot \vec{\nabla} \times \vec{\boldsymbol{B}}) + \vec{\nabla} \times \{\eta_{\mathrm{AD}} \cdot (\vec{\nabla} \times \vec{\boldsymbol{B}}) \times \vec{\boldsymbol{B}}\} - \vec{\nabla} \times [\vec{\nabla} \times \{\eta_{\mathrm{HD}} \cdot (\vec{\nabla} \times \vec{\boldsymbol{B}}) \times \vec{\boldsymbol{B}}\}]$$

… something personal …



26 June 1964, Volume 144, Number 3626

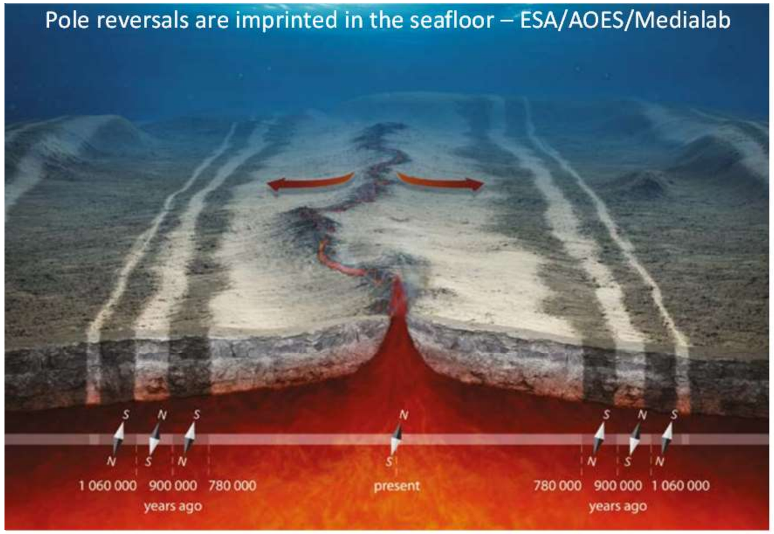
SCIENCE

Reversals of the Earth's Magnetic Field

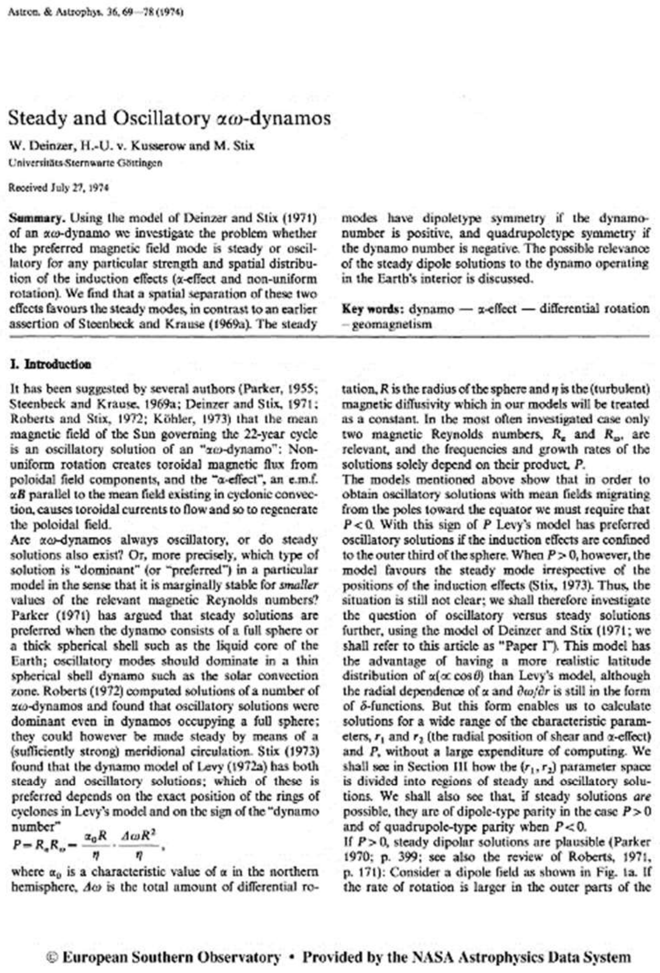
Recent paleomagnetic and geochronologic data provide information on time and frequency of field reversals.

Allan Cox, Richard R. Doell, G. Brent Dalrymple

ment in techniques of determining the stability and reliability of rock magnetism for determining past geomagnetic field directions, and partly as a result of the vast increase in paleomagnetic data available. Although many of these paleomagnetic studies have focused on the problems of continental drift and polar wandering, interest in the reversal problem has also continued up to the present, and the observations of the early workers have been amply confirmed. The directions of remanent magnetization in many tens of thousands of rock samples, with ages in the range 0 to 30 million years, show a strikingly bimodal distribution; the directions are grouped about either the



Pole reversals are imprinted in the seafloor – ESA/AOES/Medialab



Astron. & Astrophys. 36, 69—78 (1974)

Steady and Oscillatory $\alpha\omega$-dynamos

W. Deinzer, H.-U. v. Kusserow and M. Stix
Universitäts-Sternwarte Göttingen

Received July 27, 1974

Summary. Using the model of Deinzer and Stix (1971) of an $\alpha\omega$-dynamo we investigate the problem whether the preferred magnetic field mode is steady or oscillatory for any particular strength and spatial distribution of the induction effects (α-effect and non-uniform rotation). We find that a spatial separation of these two effects favours the steady modes, in contrast to an earlier assertion of Steenbeck and Krause (1969a). The steady modes have dipoletype symmetry if the dynamo-number is positive, and quadrupoletype symmetry if the dynamo number is negative. The possible relevance of the steady dipole solutions to the dynamo operating in the Earth's interior is discussed.

Key words: dynamo — α-effect — differential rotation – geomagnetism

I. Introduction

It has been suggested by several authors (Parker, 1955; Steenbeck and Krause, 1969a; Deinzer and Stix, 1971; Roberts and Stix, 1972; Köhler, 1973) that the mean magnetic field of the Sun governing the 22-year cycle is an oscillatory solution of an "$\alpha\omega$-dynamo": Non-uniform rotation creates toroidal magnetic flux from poloidal field components, and the "α-effect", an e.m.f. αB parallel to the mean field existing in cyclonic convection, causes toroidal currents to flow and so to regenerate the poloidal field.

Are $\alpha\omega$-dynamos always oscillatory, or do steady solutions also exist? Or, more precisely, which type of solution is "dominant" (or "preferred") in a particular model in the sense that it is marginally stable for *smaller* values of the relevant magnetic Reynolds numbers? Parker (1971) has argued that steady solutions are preferred when the dynamo consists of a full sphere or a thick spherical shell such as the liquid core of the Earth; oscillatory modes should dominate in a thin spherical shell dynamo such as the solar convection zone. Roberts (1972) computed solutions of a number of $\alpha\omega$-dynamos and found that oscillatory solutions were dominant even in dynamos occupying a full sphere; they could however be made steady by means of a (sufficiently strong) meridional circulation. Stix (1973) found that the dynamo model of Levy (1972a) has both steady and oscillatory solutions; which of these is preferred depends on the exact position of the rings of cyclones in Levy's model and on the sign of the "dynamo number"

$$P = R_\alpha R_\omega = \frac{\alpha_0 R}{\eta} \cdot \frac{\Delta\omega R^2}{\eta},$$

where α_0 is a characteristic value of α in the northern hemisphere, $\Delta\omega$ is the total amount of differential rotation, R is the radius of the sphere and η is the (turbulent) magnetic diffusivity which in our models will be treated as a constant. In the most often investigated case only two magnetic Reynolds numbers, R_α and R_ω, are relevant, and the frequencies and growth rates of the solutions solely depend on their product, P.

The models mentioned above show that in order to obtain oscillatory solutions with mean fields migrating from the poles toward the equator we must require that $P<0$. With this sign of P Levy's model has preferred oscillatory solutions if the induction effects are confined to the outer third of the sphere. When $P>0$, however, the model favours the steady mode irrespective of the positions of the induction effects (Stix, 1973). Thus, the situation is still not clear; we shall therefore investigate the question of oscillatory versus steady solutions further, using the model of Deinzer and Stix (1971; we shall refer to this article as "Paper I"). This model has the advantage of having a more realistic latitude distribution of $\alpha(\propto\cos\theta)$ than Levy's model, although the radial dependence of α and $\partial\omega/\partial r$ is still in the form of δ-functions. But this form enables us to calculate solutions for a wide range of the characteristic parameters, r_1 and r_2 (the radial position of shear and α-effect) and P, without a large expenditure of computing. We shall see in Section III how the (r_1, r_2) parameter space is divided into regions of steady and oscillatory solutions. We shall also see that, if steady solutions *are* possible, they are of dipole-type parity in the case $P>0$ and of quadrupole-type parity when $P<0$.

If $P>0$, steady dipolar solutions are plausible (Parker 1970; p. 399; see also the review of Roberts, 1971, p. 171): Consider a dipole field as shown in Fig. 1a. If the rate of rotation is larger in the outer parts of the

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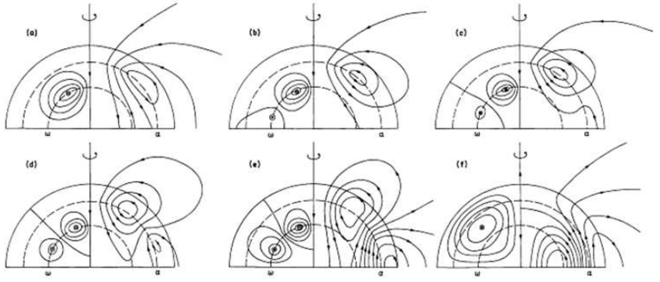


Fig. 7a–f. Meridian sections of dipolar magnetic fields, for the dynamo numbers $P=1389, 5400, 7198, 3000, 500, 0$, with α_0 and $\Delta\omega$ both positive. The corresponding eigenvalues are marked with labels a–f in Fig. 3a. The right-hand sides show the lines of force of the poloidal field, and curves of constant toroidal field strength are drawn on the left-hand sides. All contours are drawn at equal spacing of the stream function $A \cdot x \cdot \sin\theta$ on the right and the field strength B on the left. Encircled dots and crosses have the same meaning as in Fig. 1. The inner dashed circle indicates the shear surface, the outer indicates the α-effect surface. Only the northern hemisphere is shown; the fields are antisymmetric with respect to the equatorial plane

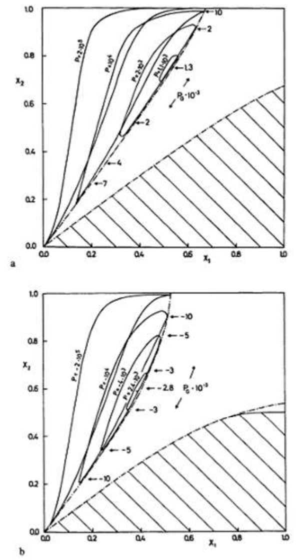


Fig. 5a and b. Curves of positive (a) and negative (b) dynamo numbers P for steady dipole (a) and quadrupole (b) solutions in the (x_1, x_2)-parameter space. The hatched region at the lower right has the same contours since the diagram is completely symmetric with respect to the line $x_1 = x_2$. In the regions between the two limiting curves oscillatory modes dominate; this is also the case within the small portion of Fig. 5b around $x_2 \approx 0.5$ and $0.75 \lesssim x_1 < 1$. Some dynamo numbers, P_G, on the limiting curves are given

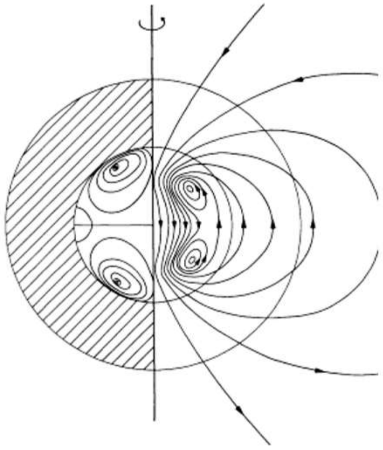


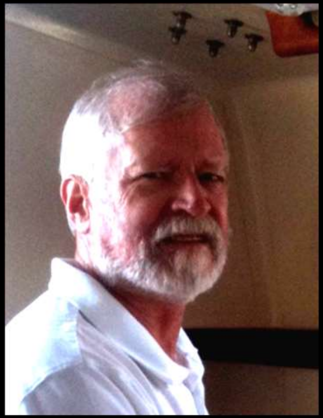
Fig. 10. The Earth as an $\alpha\omega$-dynamo, with $x_1 = 0.9$, $x_2 = 0.6$ $P_{01} = 1558$. On the left the mantle is hatched. See also the descri of Fig. 7

Willi Deinzer

Michael Stix

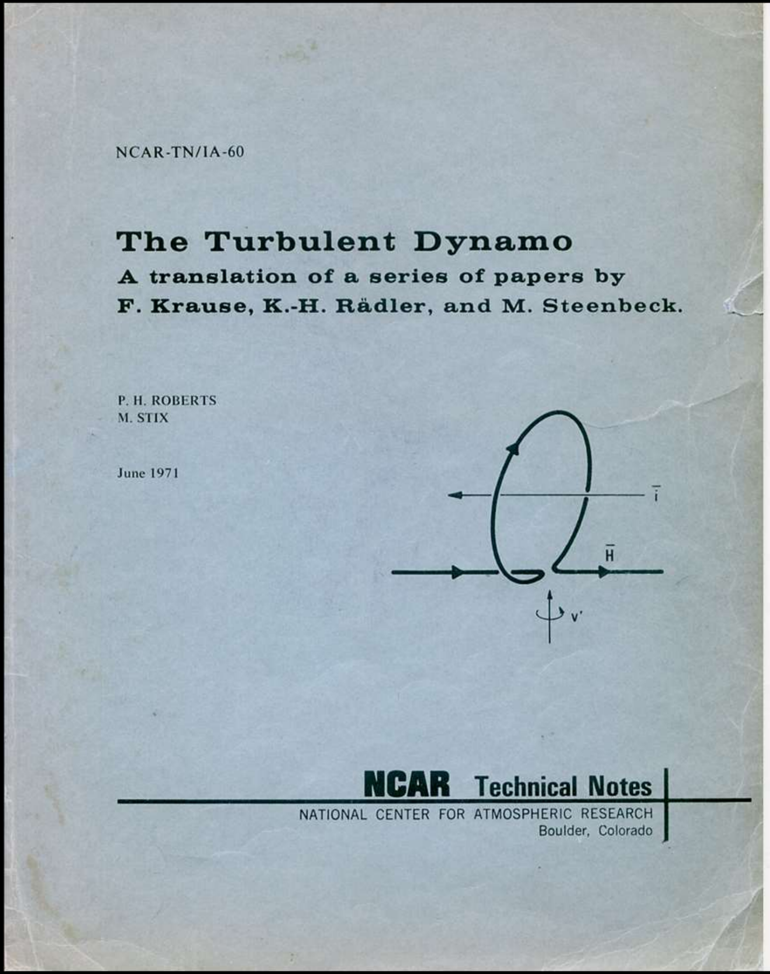
Karl-Heinz Rädler

(1935-2020)



Paul H. Roberts

(1929-2022)



NCAR-TN/IA-60

The Turbulent Dynamo

A translation of a series of papers by
F. Krause, K.-H. Rädler, and M. Steenbeck.

P. H. ROBERTS
M. STIX

June 1971

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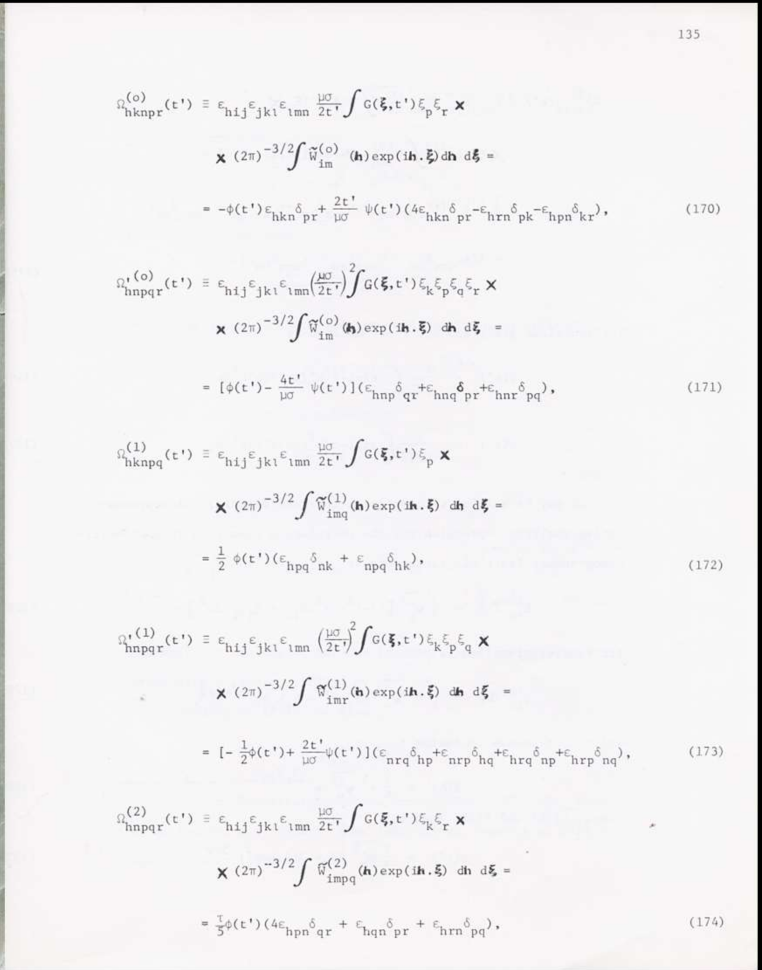


135

$$\Omega^{(o)}_{hknpr}(t') \equiv \varepsilon_{hij}\varepsilon_{jkl}\varepsilon_{lmn}\frac{\mu\sigma}{2t'}\int G(\boldsymbol{\xi},t')\xi_p\xi_r \times$$

$$\times\ (2\pi)^{-3/2}\int \tilde{W}^{(o)}_{im}(\mathbf{h})\exp(i\mathbf{h}.\boldsymbol{\xi})\,d\mathbf{h}\,d\boldsymbol{\xi} =$$

$$= -\phi(t')\varepsilon_{hkn}\delta_{pr} + \frac{2t'}{\mu\sigma}\psi(t')(4\varepsilon_{hkn}\delta_{pr} - \varepsilon_{hrn}\delta_{pk} - \varepsilon_{hpn}\delta_{kr}), \tag{170}$$

$$\Omega'^{(o)}_{hnpqr}(t') \equiv \varepsilon_{hij}\varepsilon_{jkl}\varepsilon_{lmn}\left(\frac{\mu\sigma}{2t'}\right)^2\int G(\boldsymbol{\xi},t')\xi_k\xi_p\xi_q\xi_r \times$$

$$\times\ (2\pi)^{-3/2}\int \tilde{W}^{(o)}_{im}(\mathbf{h})\exp(i\mathbf{h}.\boldsymbol{\xi})\,d\mathbf{h}\,d\boldsymbol{\xi} =$$

$$= [\phi(t') - \frac{4t'}{\mu\sigma}\psi(t')](\varepsilon_{hnp}\delta_{qr} + \varepsilon_{hnq}\delta_{pr} + \varepsilon_{hnr}\delta_{pq}), \tag{171}$$

$$\Omega^{(1)}_{hknpq}(t') \equiv \varepsilon_{hij}\varepsilon_{jkl}\varepsilon_{lmn}\frac{\mu\sigma}{2t'}\int G(\boldsymbol{\xi},t')\xi_p \times$$

$$\times\ (2\pi)^{-3/2}\int \tilde{W}^{(1)}_{imq}(\mathbf{h})\exp(i\mathbf{h}.\boldsymbol{\xi})\,d\mathbf{h}\,d\boldsymbol{\xi} =$$

$$= \frac{1}{2}\phi(t')(\varepsilon_{hpq}\delta_{nk} + \varepsilon_{npq}\delta_{hk}), \tag{172}$$

$$\Omega'^{(1)}_{hnpqr}(t') \equiv \varepsilon_{hij}\varepsilon_{jkl}\varepsilon_{lmn}\left(\frac{\mu\sigma}{2t'}\right)^2\int G(\boldsymbol{\xi},t')\xi_k\xi_p\xi_q \times$$

$$\times\ (2\pi)^{-3/2}\int \tilde{W}^{(1)}_{imr}(\mathbf{h})\exp(i\mathbf{h}.\boldsymbol{\xi})\,d\mathbf{h}\,d\boldsymbol{\xi} =$$

$$= [-\frac{1}{2}\phi(t') + \frac{2t'}{\mu\sigma}\psi(t')](\varepsilon_{nrq}\delta_{hp} + \varepsilon_{nrp}\delta_{hq} + \varepsilon_{hrq}\delta_{np} + \varepsilon_{hrp}\delta_{nq}), \tag{173}$$

$$\Omega^{(2)}_{hnpqr}(t') \equiv \varepsilon_{hij}\varepsilon_{jkl}\varepsilon_{lmn}\frac{\mu\sigma}{2t'}\int G(\boldsymbol{\xi},t')\xi_k\xi_r \times$$

$$\times\ (2\pi)^{-3/2}\int \tilde{W}^{(2)}_{impq}(\mathbf{h})\exp(i\mathbf{h}.\boldsymbol{\xi})\,d\mathbf{h}\,d\boldsymbol{\xi} =$$

$$= \frac{1}{5}\phi(t')(4\varepsilon_{hpn}\delta_{qr} + \varepsilon_{hqn}\delta_{pr} + \varepsilon_{hrn}\delta_{pq}), \tag{174}$$

P. H. Roberts, M. Stix , The Turbulent Dynamo, 1971

Hannes Alfven (1908 - 1995)

HANNES ALFVEN

Hannes Alfven Medaille

1937 Research into plasma physics, charged particle beams

1939 Theory of magnetic storms and auroras
Theory of plasma dynamics in the Earth's magnetosphere
Work on interplanetary, magnetospheric physics

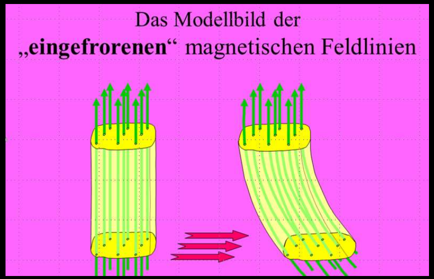
1943 Development of the theorem of the freezing of magnetic field lines in electrically highly conductive matter

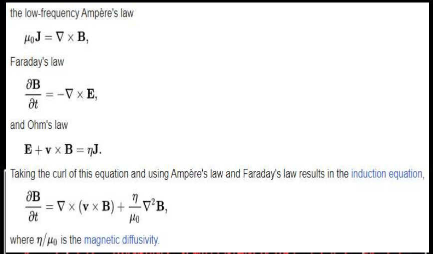
1970 Nobel Prize in Physics for fundamental achievements and discoveries in magnetohydrodynamics with fruitful applications in plasma physics

1976 Summary of his work on the influence of magnetic fields on the origin of our solar system

1987 Introduction of the term “nanoflare” to explain coronal heating

NASA


Das Modellbild der
„**eingefrorenen**“ magnetischen Feldlinien


the low-frequency Ampère's law

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B},$$

Faraday's law

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E},$$

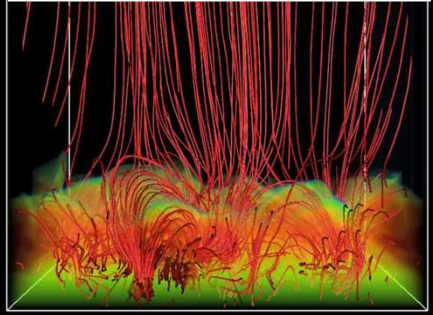
and Ohm's law

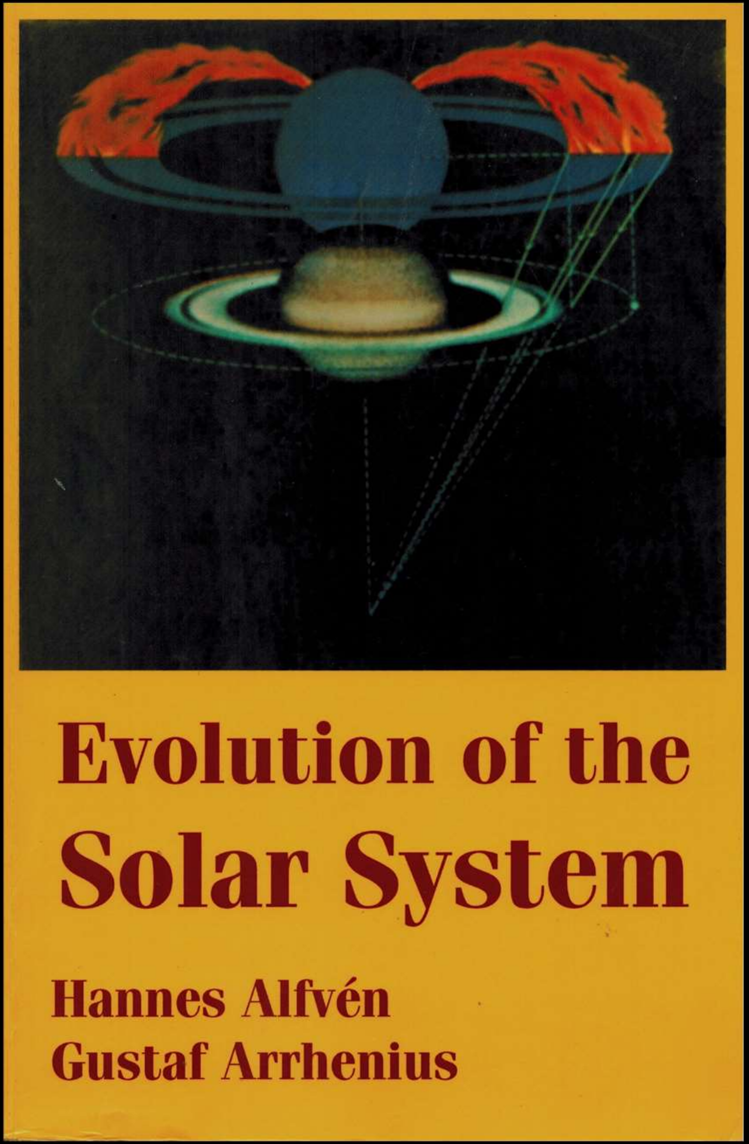
$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J}.$$

Taking the curl of this equation and using Ampère's law and Faraday's law results in the induction equation,

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{\eta}{\mu_0} \nabla^2 \mathbf{B},$$

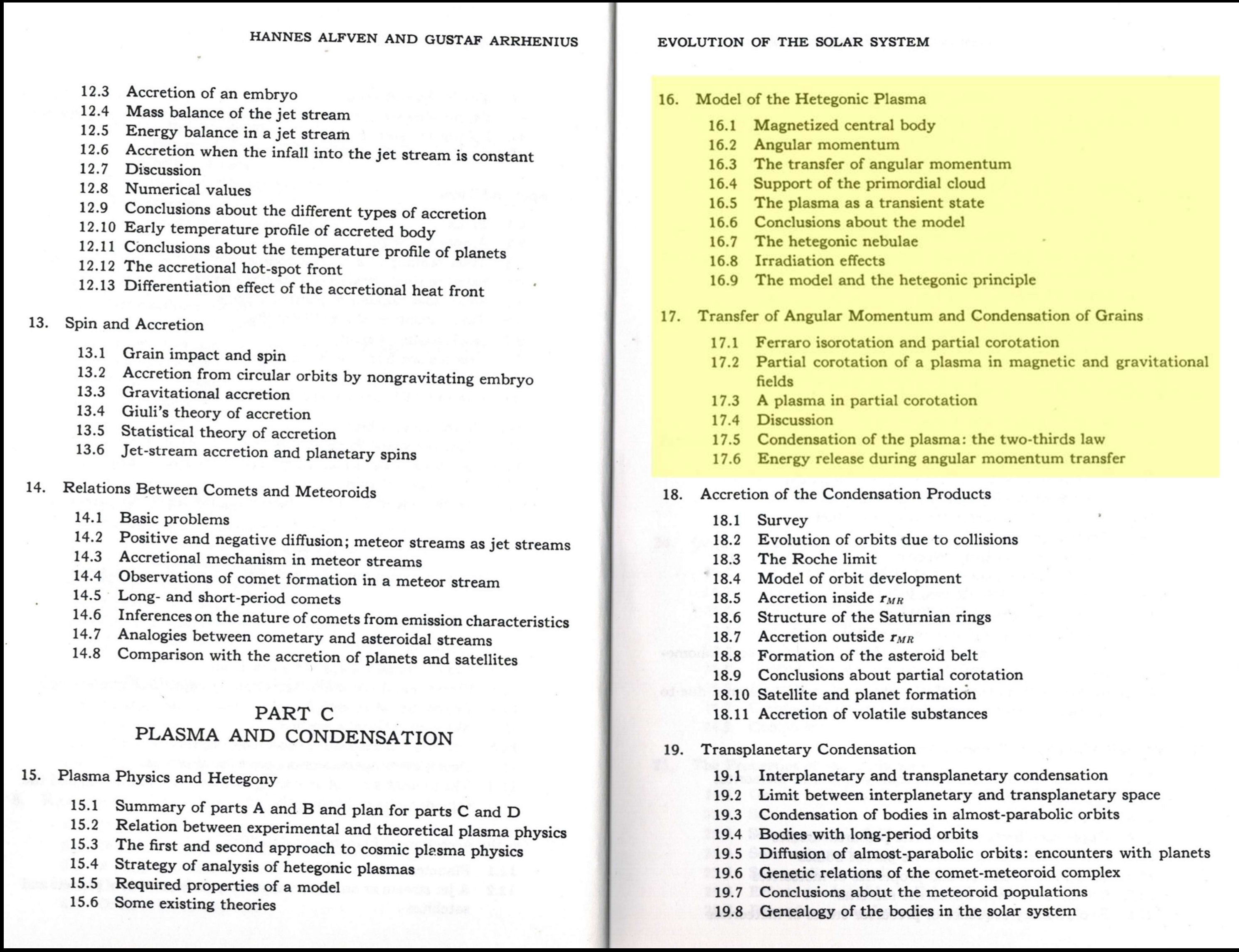
where η/μ_0 is the magnetic diffusivity.





Evolution of the Solar System

Hannes Alfvén
Gustaf Arrhenius



- 12.3 Accretion of an embryo
- 12.4 Mass balance of the jet stream
- 12.5 Energy balance in a jet stream
- 12.6 Accretion when the infall into the jet stream is constant
- 12.7 Discussion
- 12.8 Numerical values
- 12.9 Conclusions about the different types of accretion
- 12.10 Early temperature profile of accreted body
- 12.11 Conclusions about the temperature profile of planets
- 12.12 The accretional hot-spot front
- 12.13 Differentiation effect of the accretional heat front

13. Spin and Accretion
    - 13.1 Grain impact and spin
    - 13.2 Accretion from circular orbits by nongravitating embryo
    - 13.3 Gravitational accretion
    - 13.4 Giuli's theory of accretion
    - 13.5 Statistical theory of accretion
    - 13.6 Jet-stream accretion and planetary spins

14. Relations Between Comets and Meteoroids
    - 14.1 Basic problems
    - 14.2 Positive and negative diffusion; meteor streams as jet streams
    - 14.3 Accretional mechanism in meteor streams
    - 14.4 Observations of comet formation in a meteor stream
    - 14.5 Long- and short-period comets
    - 14.6 Inferences on the nature of comets from emission characteristics
    - 14.7 Analogies between cometary and asteroidal streams
    - 14.8 Comparison with the accretion of planets and satellites

PART C
PLASMA AND CONDENSATION

15. Plasma Physics and Hetegony
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    - 15.2 Relation between experimental and theoretical plasma physics
    - 15.3 The first and second approach to cosmic plasma physics
    - 15.4 Strategy of analysis of hetegonic plasmas
    - 15.5 Required properties of a model
    - 15.6 Some existing theories

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    - 16.3 The transfer of angular momentum
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    - 16.5 The plasma as a transient state
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    - 16.7 The hetegonic nebulae
    - 16.8 Irradiation effects
    - 16.9 The model and the hetegonic principle

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    - 17.3 A plasma in partial corotation
    - 17.4 Discussion
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    - 18.10 Satellite and planet formation
    - 18.11 Accretion of volatile substances

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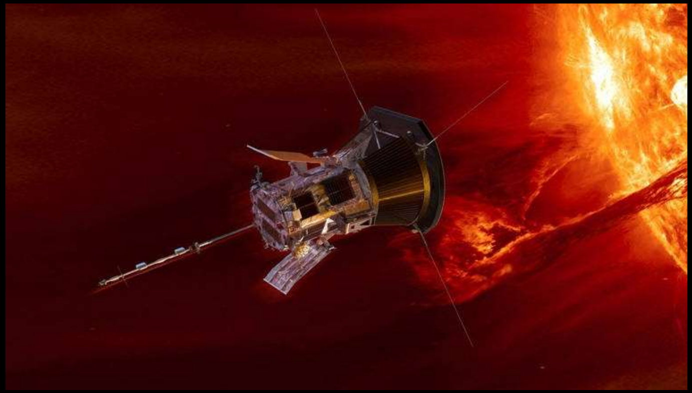
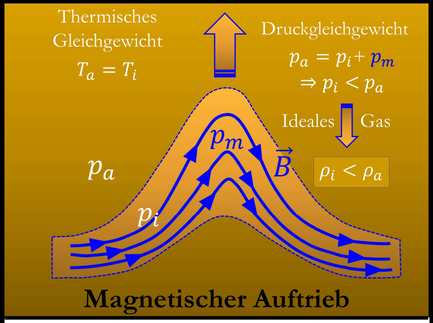
    - 19.3 Condensation of bodies in almost-parabolic orbits
    - 19.4 Bodies with long-period orbits
    - 19.5 Diffusion of almost-parabolic orbits: encounters with planets
    - 19.6 Genetic relations of the comet-meteoroid complex
    - 19.7 Conclusions about the meteoroid populations
    - 19.8 Genealogy of the bodies in the solar system

Eugene Newman Parker (1927 - 2022)

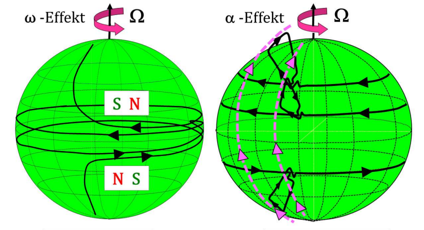


Parker Solar Probe (PSP) NASA/JHUAPL

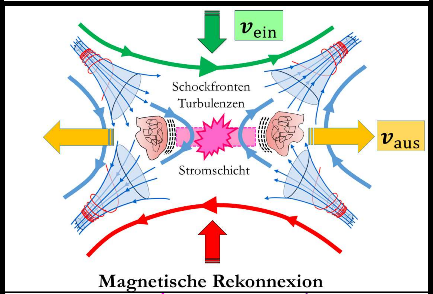
1955	Discovery of magnetic buoyancy ("Parker instability") as an upward force exerted on magnetic flux tubes subject to gravity in electrically conductive media
1955	Development of the idea that the influence of cyclonic movements (alpha effect) could be important for the function of a dynamo cycle to generate cosmic magnetic fields
1957/1958	Development of the Sweet-Parker model of magnetic reconnection
1958/1959	Development of a first magneto-hydrodynamic theory to describe the solar wind model design for the "Parker spiral"
1987	Introduction of the term "nanoflare" to explain coronal heating


Thermisches Gleichgewicht
$T_a = T_i$
Druckgleichgewicht
$p_a = p_i + p_m$
$\Rightarrow p_i < p_a$
Ideales Gas
$\rho_i < \rho_a$
p_m
$\vec{B}$
p_a
p_i

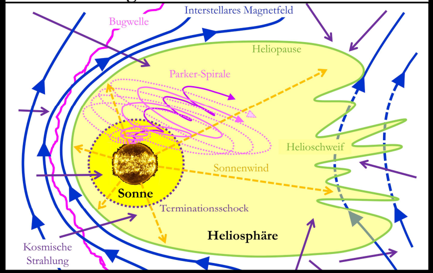
Magnetischer Auftrieb


ω -Effekt
Ω
α -Effekt
Ω
S N
N S
Differenzielle Rotation
Konvektion – Corioliskraft

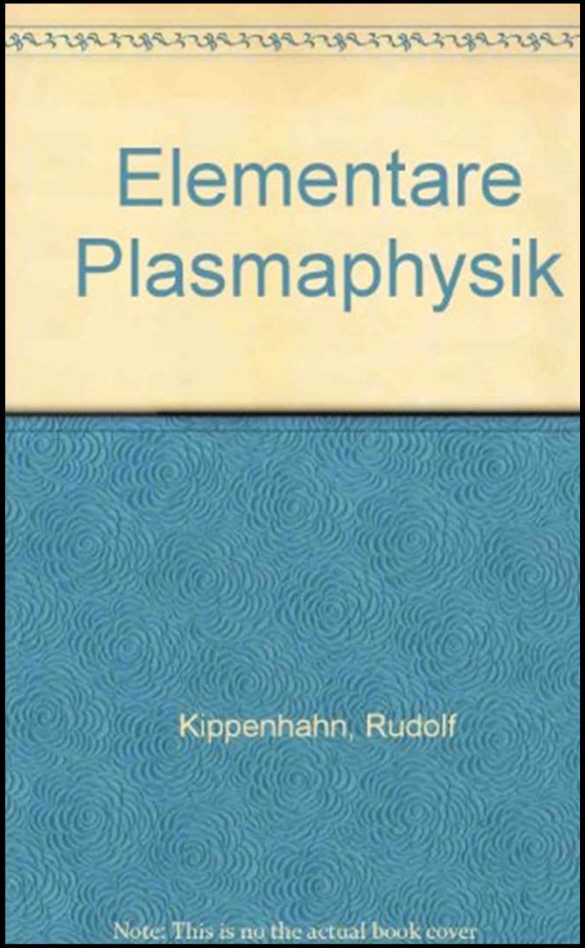
αω-Dynamo


v_{ein}
Schockfronten
Turbulenzen
v_{aus}
Stromschicht

Magnetische Rekonnexion


Interstellares Magnetfeld
Bugwelle
Heliopause
Parker-Spirale
Helioschweif
Sonnenwind
Sonne
Terminationsschock
Heliosphäre
Kosmische Strahlung

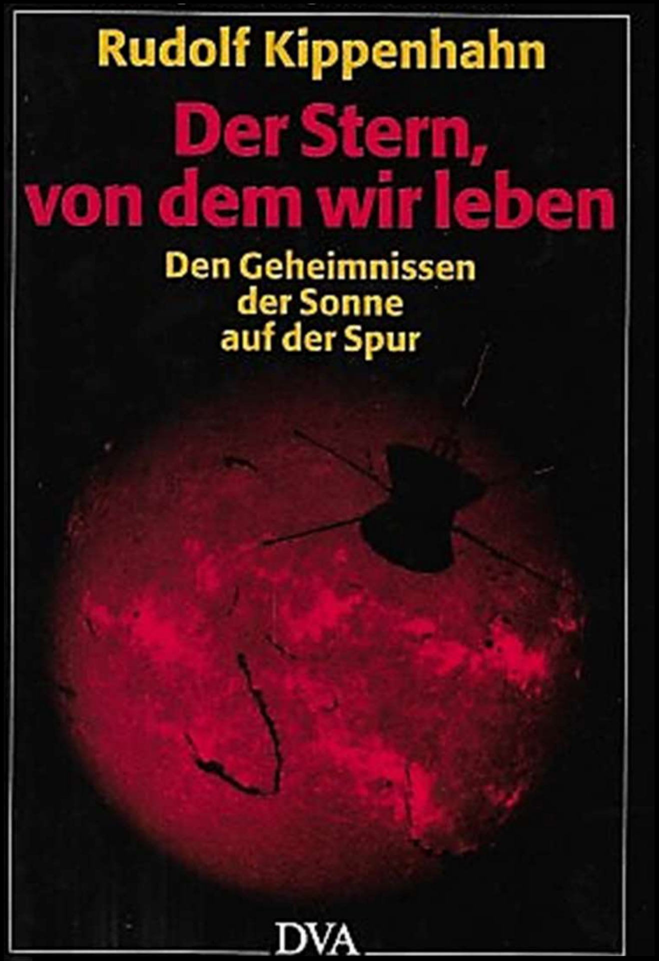
Rudolf Kippenhahn (1926-2020)



Elementare
Plasmaphysik

Kippenhahn, Rudolf

Note: This is no the actual book cover



Rudolf Kippenhahn

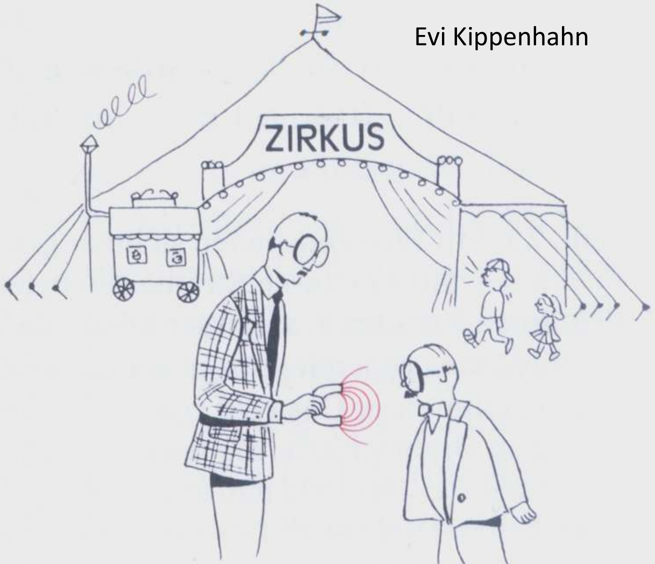
Der Stern,
von dem wir leben

Den Geheimnissen
der Sonne
auf der Spur

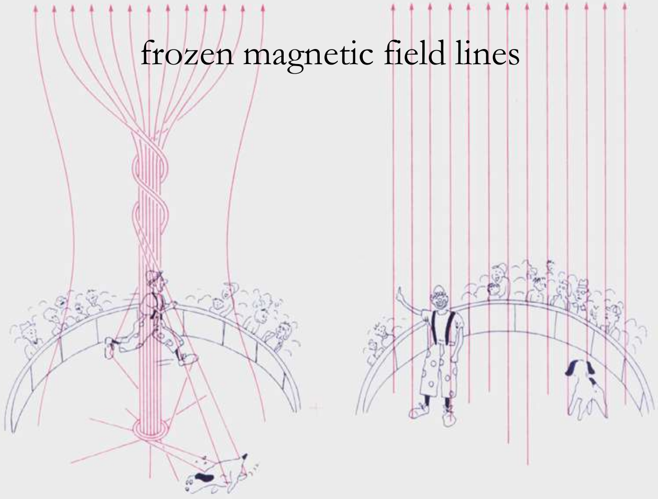
DVA

Mr. Tolkin and Mr. Meyer in the Plasmaland Circus

Evi Kippenhahn

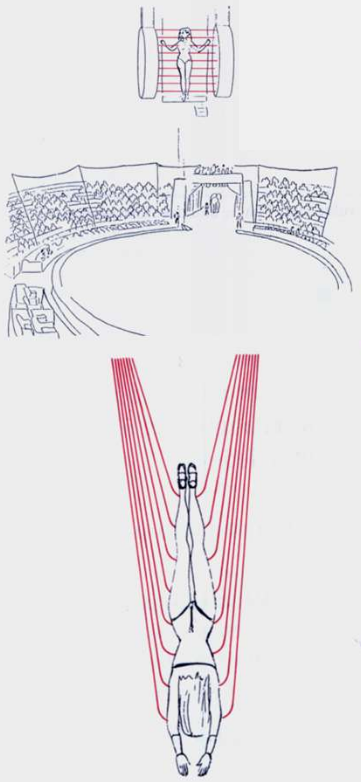


magnetic fields visible through glasses

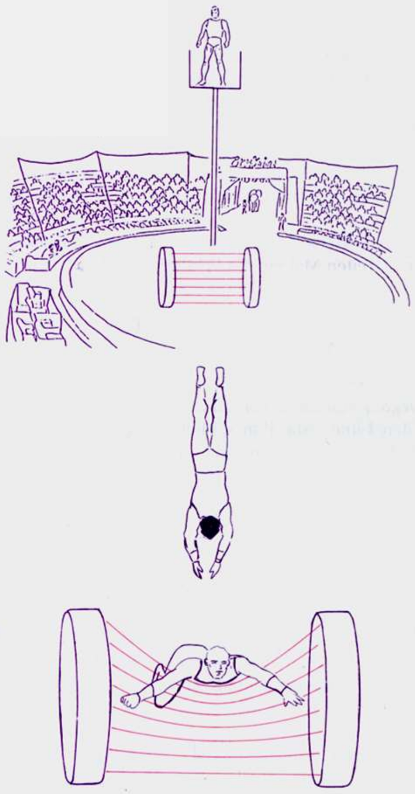


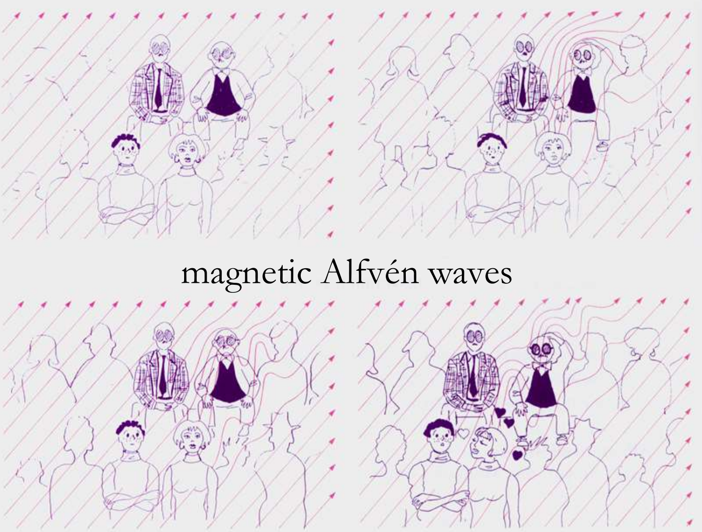
frozen magnetic field lines

magnetic tension

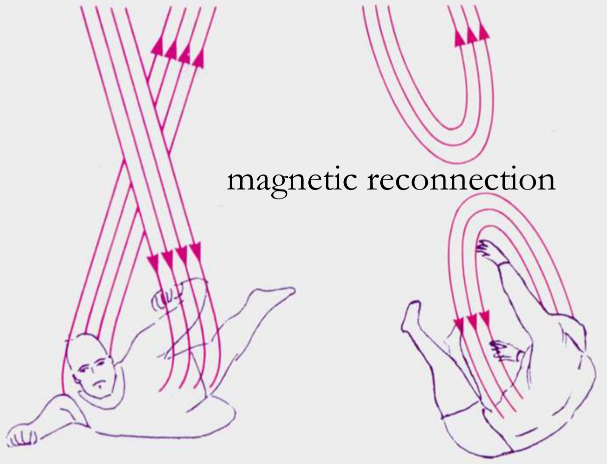


magnetic pressure





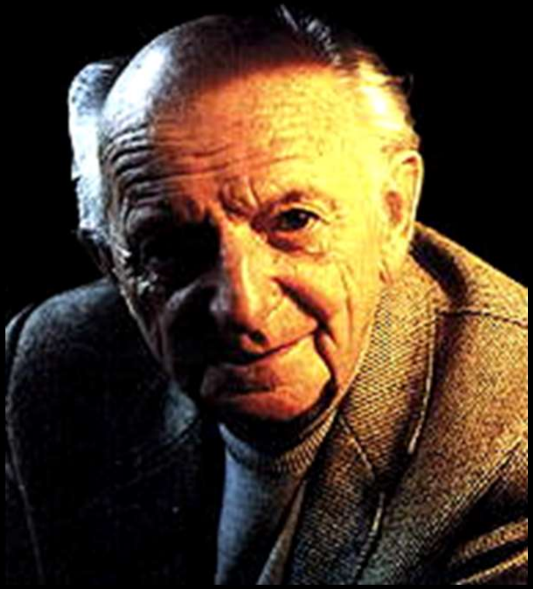
magnetic Alfvén waves



magnetic reconnection

Fundamentals of Didactic Analysis

What do you do, why and how?



Martin Wagenschein (1896 - 1988)
German Physicist and Educator

- Subject Didactics of Mathematics and Natural Sciences
- Scientific Cognitive Psychology
- Didactics of the Exact Natural Sciences
- Principle of Exemplary Learning
- Courage to leave Gaps

Wolfgang Klafki (1927 - 2016)
German Educational Scientist

- Motivations
- Addressee References
- Future Significance
- Exemplarity
- Background Structures
- Historical References

James Gre
Scottish s

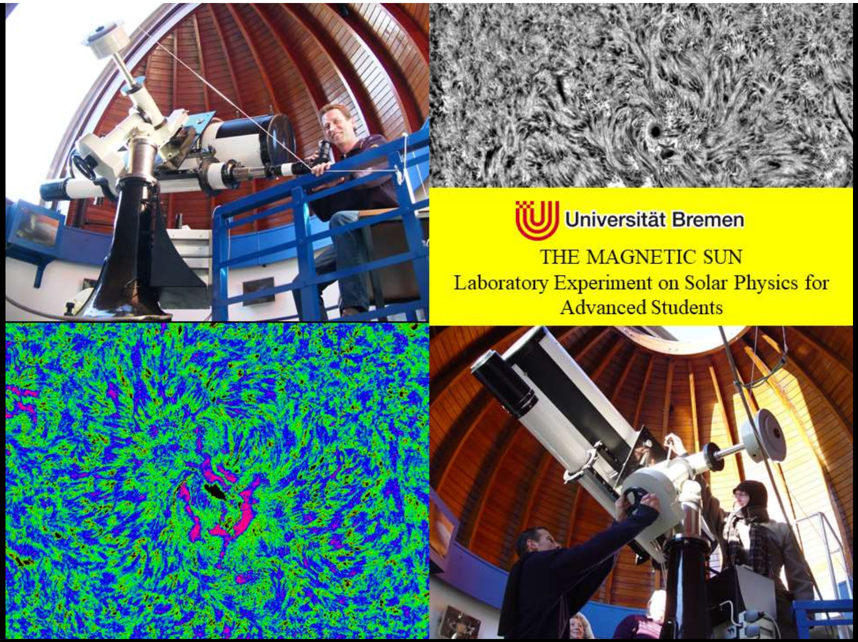
RädlerFest: α effect and beyond, Stockholm18 Feb 2011

K.-H. Rädler

… for Popular Sciences …

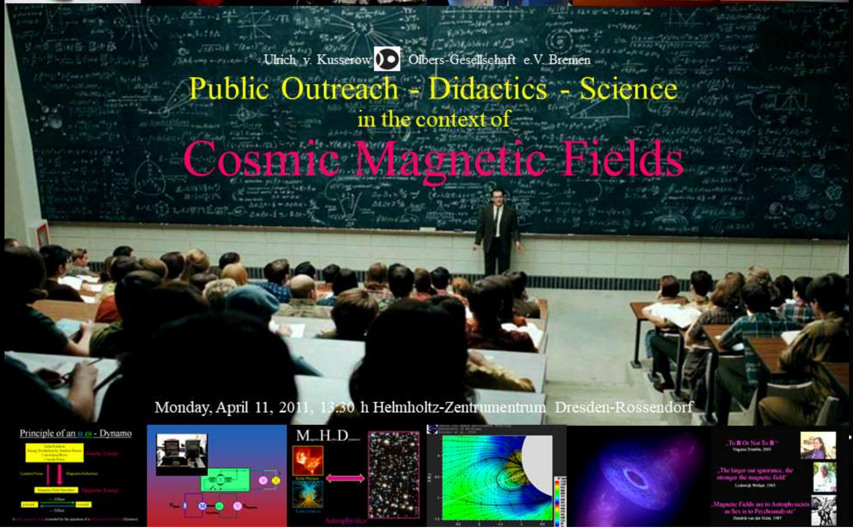
Ulrich v. Kusserow Olbers-Gesellschaft e.V. Bremen

NORDITA
erc
APOKALYPSE AUS DEM ALL
M...H..D...



Universität Bremen

THE MAGNETIC SUN
Laboratory Experiment on Solar Physics for Advanced Students

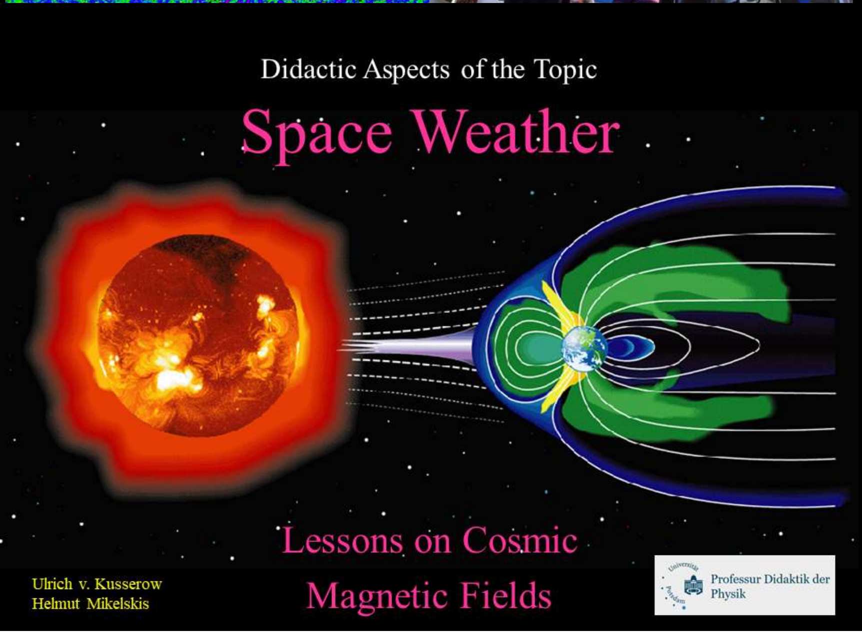


Ulrich v. Kusserow Olbers-Gesellschaft e.V. Bremen

Public Outreach - Didactics - Science
in the context of
Cosmic Magnetic Fields

Monday, April 11, 2011, 13:30 h Helmholtz-Zentrumentrum Dresden-Rossendorf

Principle of an α ω - Dynamo
M...H..D...



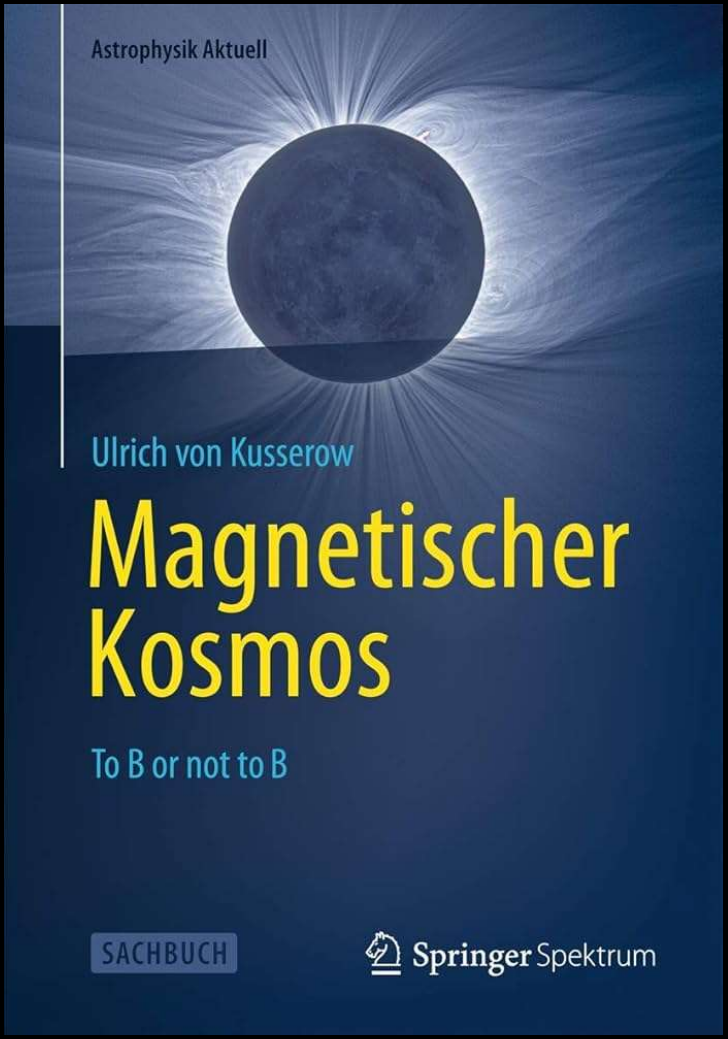
Didactic Aspects of the Topic

Space Weather

Lessons on Cosmic Magnetic Fields

Ulrich v. Kusserow
Helmut Mikelskis

Professur Didaktik der Physik



Astrophysik Aktuell

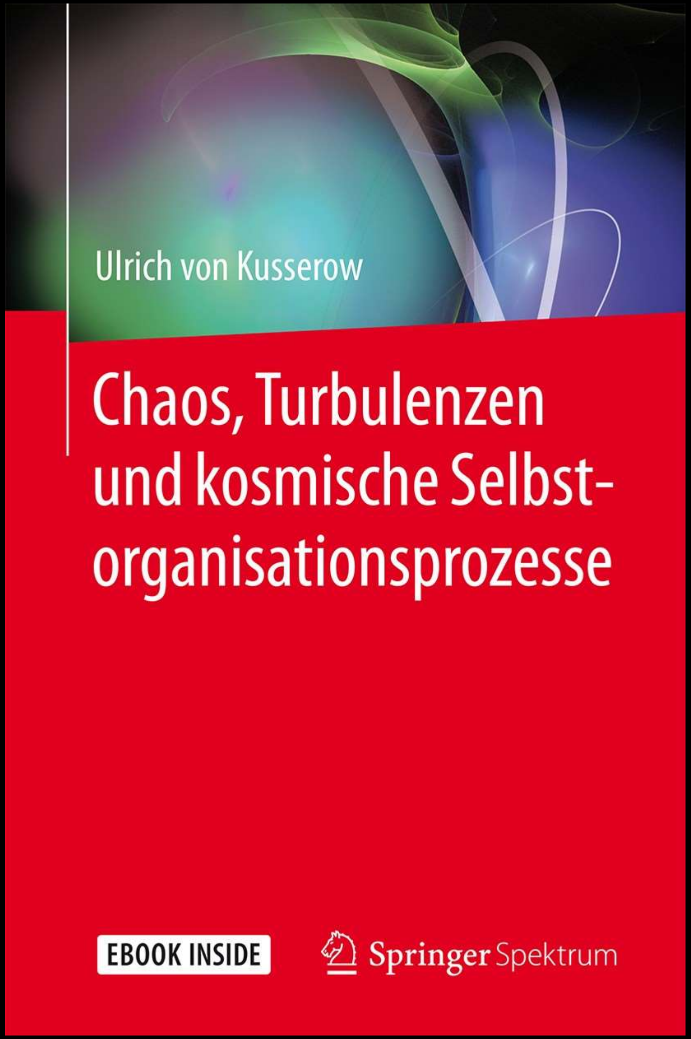
Ulrich von Kusserow

Magnetischer Kosmos

To B or not to B

SACHBUCH

Springer Spektrum



Ulrich von Kusserow

Chaos, Turbulenzen und kosmische Selbstorganisationsprozesse

EBOOK INSIDE

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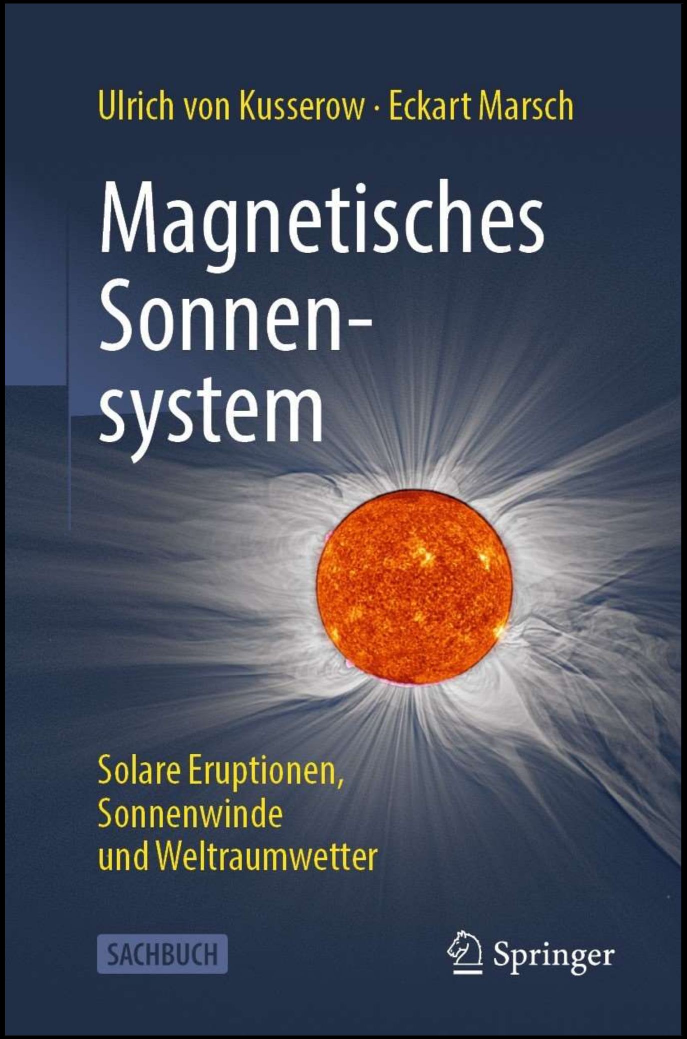

Ulrich von Kusserow · Eckart Marsch

Magnetisches Sonnensystem

Solare Eruptionen,
Sonnenwinde
und Weltraumwetter

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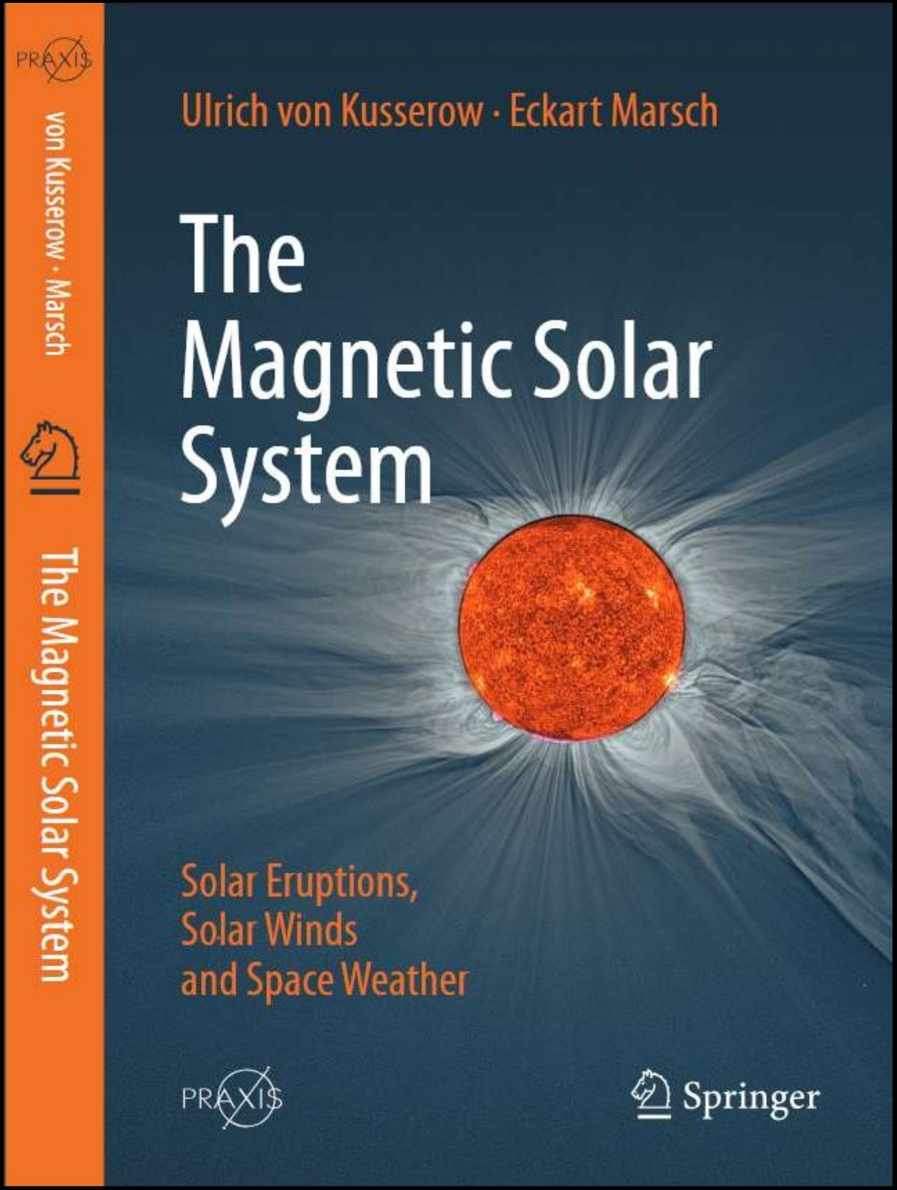

PRAXIS

von Kusserow · Marsch

The Magnetic Solar System

Ulrich von Kusserow · Eckart Marsch

The
Magnetic Solar
System

Solar Eruptions,
Solar Winds
and Space Weather

PRAXIS

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On the History of the Discovery of Solar and Heliospheric Processes

Ulrich von Kusserow

Zur Entstehung des
Magnetischen Sonnensystems

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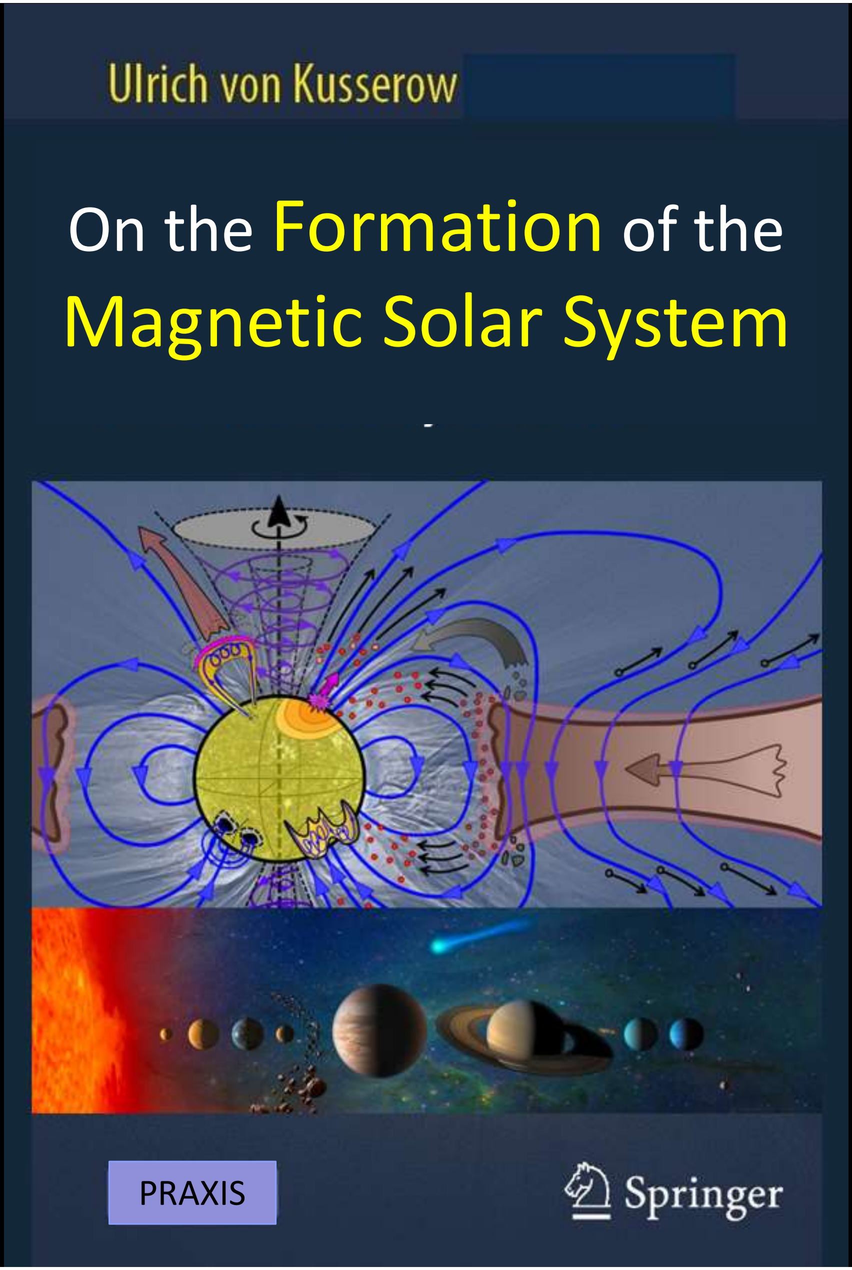
Ulrich von Kusserow

On the Formation of the
Magnetic Solar System

PRAXIS

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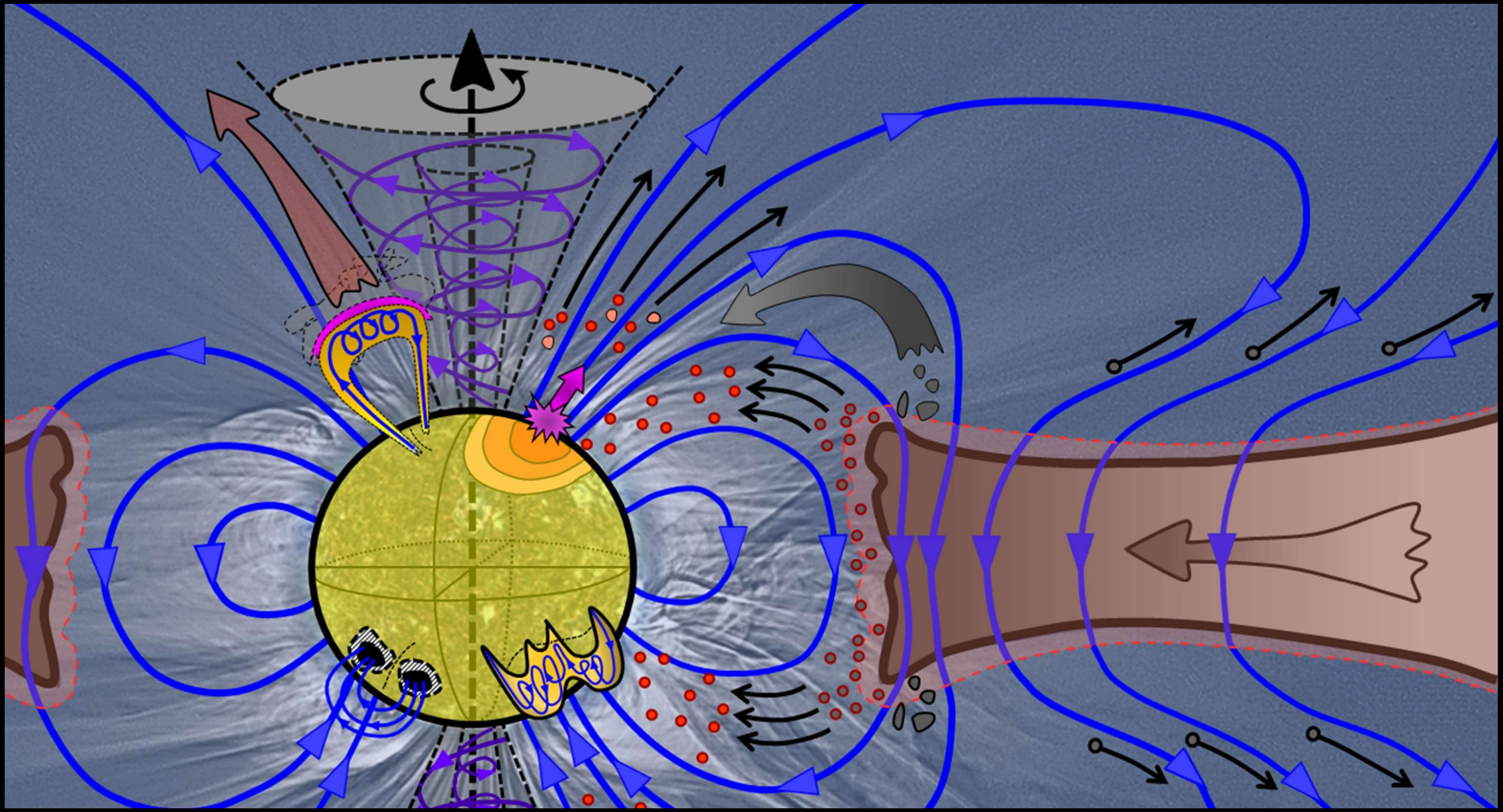
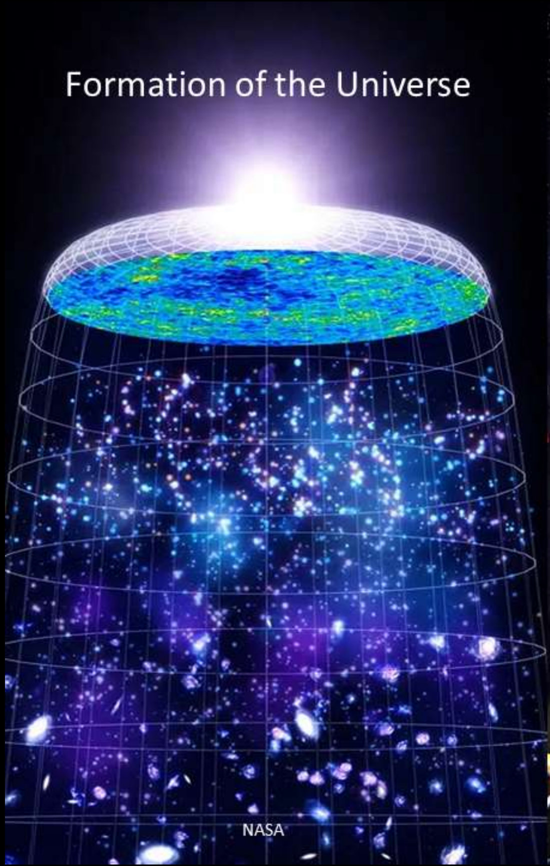


$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{B}) - \vec{\nabla} \times (\eta_{\mathrm{OD}} \cdot \vec{\nabla} \times \vec{B}) + \vec{\nabla} \times \{\eta_{\mathrm{AD}} \cdot (\vec{\nabla} \times \vec{B}) \times \vec{B}\} - \vec{\nabla} \times [\vec{\nabla} \times \{\eta_{\mathrm{HD}} \cdot (\vec{\nabla} \times \vec{B}) \times \vec{B}\}]$$

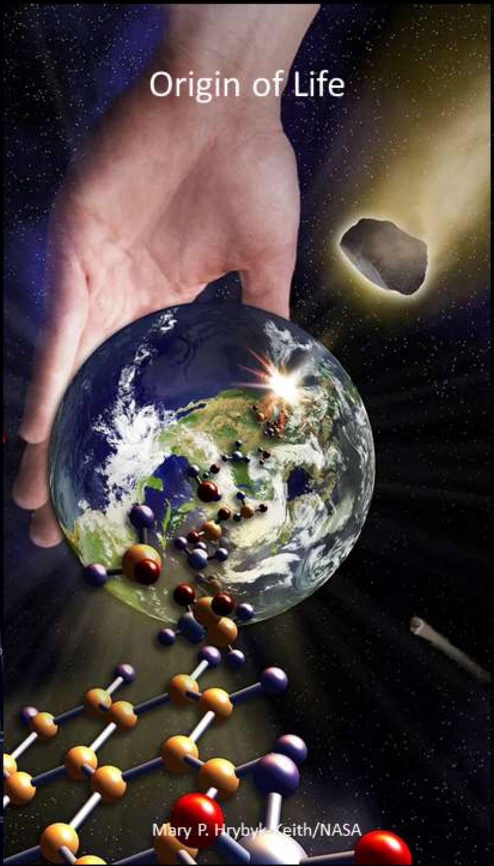
Adressee References

Adressee References

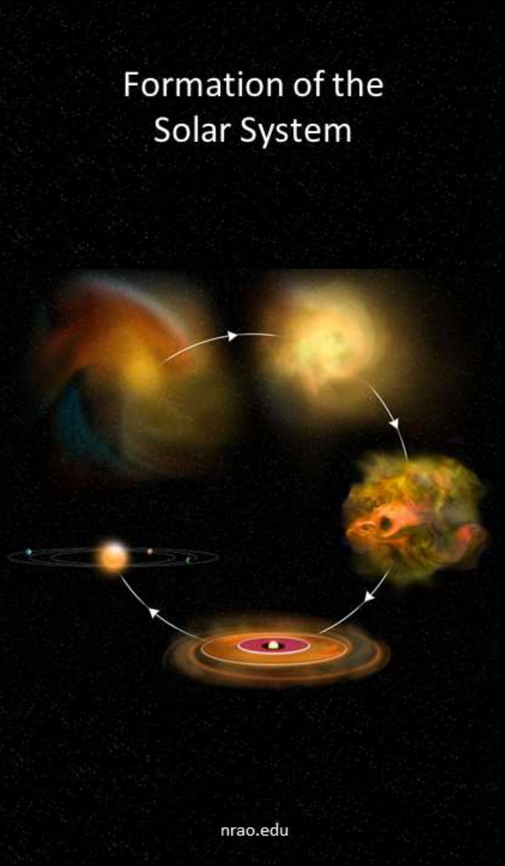
- Public Audiance
- Amateur Astronomers
- Teachers
- Students
- Scientists


Formation of the Universe

NASA


Origin of Life

Mary P. Hrybyk-Keith/NASA


Formation of the Solar System

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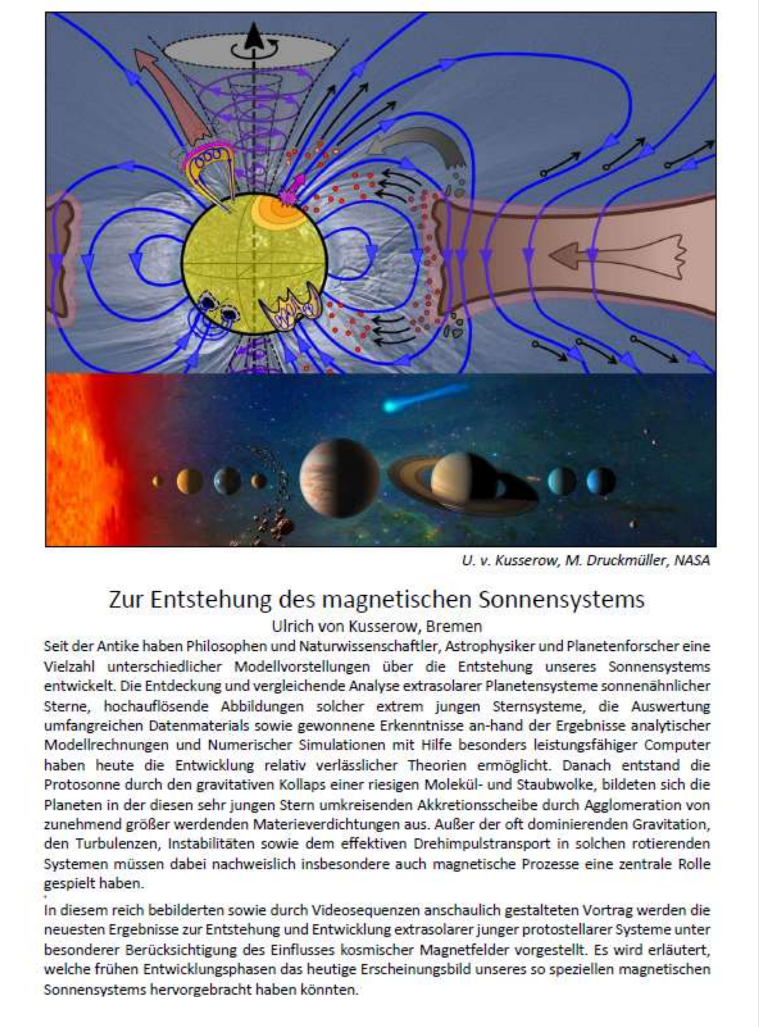

U. v. Kusserow, M. Druckmüller, NASA

Zur Entstehung des magnetischen Sonnensystems

Ulrich von Kusserow, Bremen

Seit der Antike haben Philosophen und Naturwissenschaftler, Astrophysiker und Planetenforscher eine Vielzahl unterschiedlicher Modellvorstellungen über die Entstehung unseres Sonnensystems entwickelt. Die Entdeckung und vergleichende Analyse extrasolarer Planetensysteme sonnenähnlicher Sterne, hochauflösende Abbildungen solcher extrem jungen Sternsysteme, die Auswertung umfangreichen Datenmaterials sowie gewonnene Erkenntnisse an-hand der Ergebnisse analytischer Modellrechnungen und Numerischer Simulationen mit Hilfe besonders leistungsfähiger Computer haben heute die Entwicklung relativ verlässlicher Theorien ermöglicht. Danach entstand die Protosonne durch den gravitativen Kollaps einer riesigen Molekül- und Staubwolke, bildeten sich die Planeten in der diesen sehr jungen Stern umkreisenden Akkretionsscheibe durch Agglomeration von zunehmend größer werdenden Materieverdichtungen aus. Außer der oft dominierenden Gravitation, den Turbulenzen, Instabilitäten sowie dem effektiven Drehimpulstransport in solchen rotierenden Systemen müssen dabei nachweislich insbesondere auch magnetische Prozesse eine zentrale Rolle gespielt haben.

In diesem reich bebilderten sowie durch Videosequenzen anschaulich gestalteten Vortrag werden die neuesten Ergebnisse zur Entstehung und Entwicklung extrasolarer junger protostellarer Systeme unter besonderer Berücksichtigung des Einflusses kosmischer Magnetfelder vorgestellt. Es wird erläutert, welche frühen Entwicklungsphasen das heutige Erscheinungsbild unseres so speziellen magnetischen Sonnensystems hervorgebracht haben könnten.

Adressee References

- Public Audiance
- **Amateur Astronomers**
- Teachers
- Students
- Scientists

LDN 1471: A Windblown Star Cavity - HST , NASA, ESA; Processing & License: Judy Schmidt

Adressee References

- Public Audiance
- **Amateur Astronomers**
- Teachers
- Students
- Scientists

Ulrich von Kusserow, Bremen
Entstehung des magnetischen Sonnensystems

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ASTRONOMIE
+RAUMFAHRT
im Unterricht

195

Einführungsthemen für den Astronomieunterricht

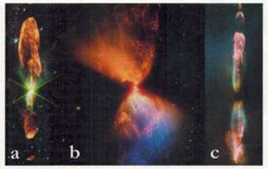
- Sternentwicklung und das HRD
- Entstehung des magnetischen Sonnensystems
- Die Erfindung des Fernrohrs
- Weiße Zwerge im Schulunterricht

FRIEDRICH

Über die Entstehung des magnetischen Sonnensystems (3)

von Ulrich von Kusserow

Materie- und Drehimpulstransportprozesse unter Einfluss magnetischer Kraftfelder bestimmen die Entwicklung insbesondere auch sonnenähnlicher protostellarer Systeme. Sie ermöglichen den Massezuwachs sowie die notwendige Abbremsung anfangs zunehmend schneller rotierender prästellare Sterne. Sie bewirken die Ausbildung der sie umlaufenden Akkretionsscheiben, in denen die Gas- und Staubmaterie turbulent verwirbelt werden kann, in denen sie Migrationsbewegungen durchführt und in deren Äquatorbereich sie sich schließlich zu präplanetaren Objekten verdichten lässt. In den Scheiben transportierte und dynamogenerierte Magnetfelder sorgen für den dafür erforderlichen Materie- und Drehimpulstransport durch einsetzende Instabilitäten sowie durch abströmende Scheibenwinde, die magnetisch generiert, beschleunigt und gelenkt werden. Erkenntnisse aus Beobachtungen, analytischen Modellierungen und numerischen Simulationen extrasolarer prostellarer Sternsysteme sowie aus Laborexperimenten ermöglichen heute tiefere Erkenntnisse über die frühe Entstehungsgeschichte auch unseres Sonnensystems.
Teil 1 und 2 dieser Reihe erschienen in ASTRONOMIE+RAUMFAHRT im Unterricht Heft 1/2024, S. 18–24 bzw. Heft2/2024, S. 17–26.

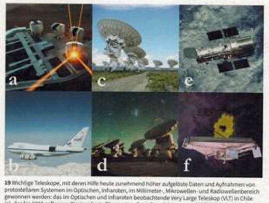


18 Infrarot-Aufnahmen des James-Webb-Weltraumteleskops von Sternwinden und Herbig-Haro-Objekten protostellarer Systeme: Herbig-Haro-Objekte HH 46/47 eines Komplexes aus mehreren neugeborenen Sternen in einer Bok-Kugel in der Nähe des Gum-Nebels (**a**), Auswürfe eines protostellaren Systems in der Dunkelwolke L 1527 der Taurus-Sternbildungsregion. (**b**), jetartig kollimierte bipolare Windstrukturen im Herbig-Haro-Objekt HH 211 im Perseus, in denen Bugschocks knotenartige Aufhellungen erzeugen (**c**) *NASA/ESA/CSA/STScI/J. DePasquale/A. M. Koekemoer, J. DePasquale/A. Pagan/A. M. Koekemoer, T. Ray (DIAS Dublin)*

Unser Sonnensystem entstand sehr wahrscheinlich in einer filamentartigen Verdichtung einer riesigen galaktischen, von Magnetfeldern durchsetzten Molekülwolke ([21], [22]), ursprünglich sicherlich zeitgleich mit einer Vielzahl anderer protostellarer Systeme mit unterschiedlichen Massen gemeinsam innerhalb eines jungen Sternhaufens. Magnetische Turbulenzen und lokale Verdichtungen, Ausflüsse, Jets und Sternwinde, die von benachbarten jungen Sternen ausströmten, sowie Schockfronten von Supernova-Explosionen besonders massereicher, sich sehr schnell entwickelnder Sterne könnten bereits eine effektive Fragmentation der großen Molekülwolke bewirkt haben. Auch wenn ein Großteil der Sterne in unserer Milchstraße heute in Doppel-, Triple- und noch höherkomponentigen Systemen anzutreffen sind, so können stellare Gezeitenkräfte und Kollisionsprozesse schon frühzeitig für den Hinauswurf einzelner Protosterne mit den sie umgebenden protostellaren Scheiben aus der Wolke gesorgt haben. Vielleicht hat sich so auch das frühe Sonnensystem ohne großen Einfluss benachbarter Sternsysteme schon relativ früh und weitgehend unbehindert als Einzelsternsystem entwickeln können.

Entwicklungen, Fortschritte und Grenzen der Erkenntnisgewinnung

Eine Vielzahl moderner Großteleskope mit besonders leistungsfähigen Instrumenten ermöglichten in den vergangenen drei Jahrzehnten die Gewinnung zunehmend höher aufgelöster und sensitiverer Daten und Abbildungen protostellarer Systeme in ganz unterschiedlichen Wellenbereichen des elektromagnetischen Spektrums. Als besonders spektakulär erweisen sich die kürzlich vom 6-m-James-Webb-Weltraumteleskop (JWST, **Bild 19f**) der NASA gemachten Infrarot-Aufnahmen, die tiefere Einblicke in die komplexe und turbulent verwirbelte Struktur der Herbig-Haro-Objekte und Sternwinde solcher jungen Sternsysteme gewähren. **Bild 18a** zeigt die als HH 46/47 benannten bipolaren Materieauswürfe im Umfeld mehrerer benachbarter Protosterne, die nach einigen hunderttausend Jahren in einer als Bok-Globule bezeichneten, mit Staub und Gas gefüllten, isoliert abgegrenzt kleinen Dunkelwolke neugeboren wurden. Während diese Auswürfe ebenso wie die des relativ jungen Herbig-Haro-Objektes HH 211 in **Bild 18c** stärker kollimiert sind und im Innern knotenartige Aufhellungen aufweisen, sind die von einer schmalen Akkretionsscheibe in der Taurus Dunkelwolke L 1527 ausgehenden leuchtenden Windstrukturen (**Bild 18b**) demgegenüber weiträumiger, kegelförmig aufgefächert strukturiert.



19 Wichtige Teleskope, mit deren Hilfe heute zunehmend höher aufgelöste Daten und Aufnahmen von protostellaren Systemen im Optischen, Infraroten, im Millimeter-, Mikrowellen- und Radiowellenbereich gewonnen werden: das im Optischen und Infraroten beobachtende Very Large Teleskop (VLT) in Chile (a), das bis 2022 geflogene Stratospheric Observatory For Infrared Astronomy (SOFIA) (b), das interferometrisch arbeitende Karl G. Jansky Very Large Array (VLA) Radioteleskop in New Mexico (c), das Atacama Large Millimeter/submillimeter Array (ALMA) in mehr als 4500 m Höhe in Chile (d), das im Optischen und nahen Infraroten aus der Erdumlaufbahn beobachtende Hubble Weltraumteleskop (HST) (e) sowie das im 2. Lagrangepunkt auf der sonnenabgewandten Seite der Erde Infrarotaufnahmen erzeugende James-Webb-Weltraumteleskop (JWST) (f). *ESO, NASA/DLR, Wikipedia, ESO, NASA, NASA*

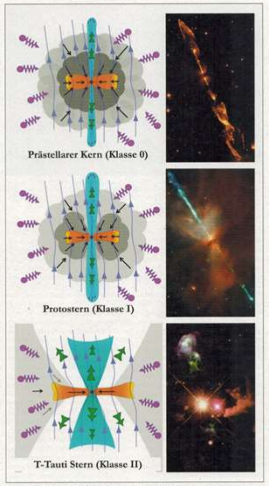
Lyman Spitzer
(1914-1997)
Telemachos Mouschovias
John Hawley
(1958-2021)
Hendrik Spruit
Leon Mestel
(1927-2017)
Nikolay Shakura
Rashid Sunyaev
Roger Blandford
Matthew R. Bate
Frank H.-S. Shu
(1943-2023)
Steven Andrew Balbus
David G. Payne
Axel Brandenburg

20 Pioniere der theoretischen Erforschung protostellarer Systeme: *Lyman Spitzer* und *Leon Mestel* sowie *Frank Shu* und *Telemachos Mouschovias* haben die Grundlagen zur analytischen Modellierung des Molekülwolkenkollapses, der magnetischen Bremsung und Ambipolaren Diffusion erforscht. *Nikolay Shakura* und *Rashid Sunyaev*, *Steven Balbus* und *John Hawley* sowie *Roger Blandford* und *David Payne* haben mit viskoser Reibung, der Magnetorotationsinstabilität bzw. mit dem Einfluss von Scheibenwinden den für effektiven Transport und die Verdichtung von Materie in Akkretionsscheiben erforderlichen Drehimpulstransport erklärt. Neben sehr vielen anderen Astrophysikern haben auch *Hendrik Spruit*, *Matthew Bate* und *Axel Brandenburg* wertvolle Beiträge zur Erforschung magnetischer Prozesse bei der Entwicklung protostellarer Systeme mit Hilfe analytischer und numerischer Simulationen geliefert. *NASA APPEL Knowledge Services, The Royal Society, Wikipedia, University of Illinois, College of Liberal Arts & Sciences Department of Astronomy, MPA, Creative Commons, Don Addison, University Communications/University of Virginia, Roger Blandford, Google Scholar, MPA, University of Exeter, IAC*

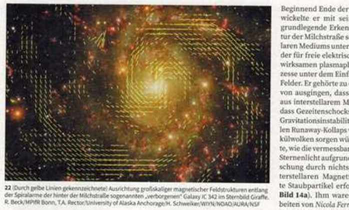
Bis Ende 2022 waren die Datengewinnung im Infraroten, insbesondere auch Magnetfeldmessungen (siehe **Bild 13b**) mit dem Stratospheric Observatory For Infrared Astronomy (SOFIA, **Bild 19b**) der NASA und des DLR (Deutsches Zentrum für Luft- und Raumfahrt) von Bord einer umgebauten Boeing 747-SP möglich. Relativ ungestört von der darunterliegenden, Infrarotstrahlung absorbierenden Atmosphäre konnten junge Sternsysteme kontinuierlich mehrere Stunden lang aus 12 bis 15 km Höhe mit einem Teleskop der freien Öffnung von 2,5 m durch ein Teleskop-Fenster beobachtet werden. Hochauflösende Aufnahmen im nahen Infraroten können auch mit dem Very Large Telescope (VLT, **Bild 19a**) der Europäischen Südsternwarte (ESO) gemacht werden (siehe auch **Bild 21, oben**), das mit vier 8,2-m- sowie weiteren 1,8-m- Hilfsteleskopen insbesondere auch im Interferometer Betrieb hochaufgelöst arbeiten kann. Auch mit dem Hubble-Weltraumteleskop (HST, **Bild 19e**) sind Beobachtungen im nahen Infraroten möglich. Ebenso wie mit dem VLT werden auch mit dem HST häufiger Aufnahmen im sichtbaren Wellenlängenbereich gemacht (siehe z. B. **Bild 8** und **Bild 21, mittig** und **unten**).

Aufnahmen sowie die Datengewinnung in speziellen Spektrallinien oder ausgedehnteren Frequenzbändern in sichtbaren und infraroten Wellenlängenbereichen ermöglichen die anschauliche Darstellung sowie tiefere Erkenntnisse über die physikalischen und chemischen Eigenschaften und Entwicklungen protostellarer Scheibe-Jet-Systeme um junge, sonnenähnliche Protosterne. Besonders hochenergetische Strahlung, die beim Auftreffen stark beschleunigter Materie aus der Akkretionsscheibe entlang stellarer magnetosphärischer Felder bevorzugt auf die polnahen Oberflächenbereiche junger Sterne in Form protostellarer Flares freigesetzt wird, kann im UV-Bereich z. B. mit dem Hubble-Weltraumteleskop der NASA und im Röntgenbereich mit dem XMM-Newton-Teleskop der ESA registriert werden. Die Datengewinnung zur Interpretation entscheidender Vorgänge in den Molekülwolken und den Akkretionsscheiben besonders junger protostellarer, später auch als protoplanetar bezeichneter Systeme erfordert dagegen die Beobachtung im Radio- bzw. Mikro- oder Millimeterwellenbereich. Sehr hohe Auflösung und große Sensitivität der gewonnenen Daten lässt sich dadurch erreichen, dass mehrere Teleskope im sogenannten Interferometrie-Modus zusammengeschaltet arbeiten. Dies gilt insbesondere für die Radioteleskope des (Karl G. Jansky) Very Large Array (VLA, **Bild 19c**) und des Atacama Large Millimeter/submillimeter Array (ALMA, **Bild 19d**).

Leider befinden sich die unserem Sonnensystem nächstgelegenen sonnenähnlichen protostellaren Systeme in allzu großer Entfernung, als dass man die relevanten physikalischen Prozesse in deren Inneren und in den, den Protosternen nahen Akkretionsscheiben-Bereichen zufriedenstellend hochaufgelöst beobachten könnte. So befinden sich die zwei jungen Doppelsterne von IRAS 16293-2422 als dem nächstgelegenen protostellaren System mit geringer Masse, das physikalisch und chemisch einigermaßen gut charakterisiert werden konnte, in einer Entfernung von etwa 460 Lichtjahren (≈2,9 · 10^7AE). Der Abstand der beiden Sterne dieses Systems mit einer Gesamtmasse von rund vier Sonnenmassen, deren Alter heute noch unbestimmt ist, beträgt etwa 750 AE. Beobachtungen der Staubscheiben durch ALMA mit einem Auflösungsvermögen von einigen AE in der Entfernung dieses jungen Sternsystems lassen vermuten, dass die Radien dieser Scheiben etwa 30-60 AE betragen. Um die Prozesse im nahen Umfeld beider Protosterne bis zum inneren Rand ihrer Akkretionsscheiben, im Abstand zwischen etwa 0,01 und 1 AE von der Sternoberfläche, wirklich auflösen zu können, dafür reicht das Auflösungsvermögen von ALMA nicht aus. Hier zeigen sich die Grenzen der Erkenntnisgewinnung, was die Beobachtungsmöglichkeiten betrifft, überdeutlich auf.



21 Schematische Darstellungen sowie reale typische Erscheinungsbilder junger protostellarer Systeme in zeitlich aufeinanderfolgenden Entwicklungsphasen (0, I und II). *U. v. Kusserow, ESO/M. J. McCaughrean, ESA/Hubble & NASA, B. Nisini, NASA and The Hubble Heritage Team (AURA/STScI).*



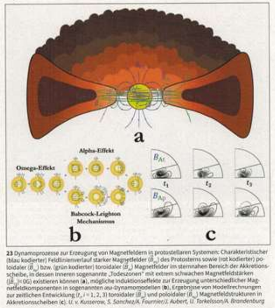
22 (Durch gelbe Linien gekennzeichnete) Ausrichtung großskaliger magnetischer Feldstrukturen entlang der Spiralarme der hinter der Milchstraße sogenannten „verborgenen" Galaxy IC 342 im Sternbild Giraffe. R. Beck/MPIfR Bonn, T.A. Rector/University of Alaska Anchorage/H. Schweiker/WIYN/NOAO/AURA/NSF

Jahrzehnte, bevor die Strukturen protostellarer Systeme in den 1990er Jahren vor allem durch den Einsatz des Hubble-Weltraumteleskops der NASA und später auch des Very Large Telescope der ESO wesentlich höher aufgelöst werden konnten, hatten theoretische Astrophysiker bereits anspruchsvolle Modellvorstellungen über die darin vermutlich ablaufenden physikalischen Prozesse entwickelt. Basierend auf ersten Beobachtungsergebnissen aus früheren Jahrhunderten sowie bekannten physikalischen Gesetzen kreierten die Wissenschaftler zunächst bildhaft anschauliche Vorstellungen über die mögliche Wirkungsweise der Gravitationskraft in rotierenden Systemen, über den Einfluss von Strahlungs- und Heizungsprozessen und von Magnetfeldern sowie über die Wechselbeziehungen dieser Einflussfaktoren untereinander, um die Vorgänge in den Molekülwolken, bei der Ausbildung von Protosternen, Akkretionsscheiben und Materieausflüssen aus diesen Systemen sowie bei der Entstehung der Planeten besser zu verstehen. Beginnend in den 1950er Jahren konnten als relevant erkannte mathematisch-physikalische Gleichungen erfolgreich zunächst algebraisch miteinander verknüpft werden, um anhand dabei rein rechnerisch gewonnener Aussagen die möglichen Wirkungszusammenhänge besser zu verstehen.

Nachdem in den 1960er Jahren erstmals Computer eingesetzt werden konnten, wurden zunächst analytische Modellrechnungen durchgeführt. Hierbei werden die Gleichungen eines zu lösenden Differentialgleichungssystems solange umgeformt, bis danach isoliert darstellbare physikalische Messgrößen in Abhängigkeit von unterschiedlichen Anfangs- und Randbedingungen numerisch mit Hilfe leistungsfähiger Rechner in systematischer Weise ermittelt werden können. Beginnend nur wenige Jahrzehnte später übernahmen dann zeitaufwendigere und teurere numerische Simulationsrechnungen die Aufgabe, auch wesentlich komplexere Probleme zu lösen. Mit Parametern gefüttert, die beispielsweise in vorangegangenen einfacheren analytischen Modellrechnungen ermittelt wurden, werden hierbei Lösungen des grundlegenden Gleichungssystems mit Hilfe besonders leistungsfähiger Computersysteme direkt ermittelt. Neben der Gewinnung räumlich, zeitlich und spektral hochaufgelöster Daten mit Hilfe von Teleskopen, analytischen sowie numerischen Modellrechnungen können heute auch analog zu kosmischen Vorgängen gestaltete Laborexperimente wertvolle Daten für die Gewinnung tieferer Erkenntnisse über die Entwicklung sonnenähnlicher protostellarer Systeme liefern.

Lyman Spitzer (1914–1997, **Bild 20**) war der „Vater" des Hubble-Weltraumteleskop-Projekts und Namensgeber des 2020 abgeschalteten, im Infraroten arbeitenden Spitzer-Weltraumteleskops. Beginnend Ende der 1940er Jahre, entwickelte er mit seinen Mitarbeitern grundlegende Erkenntnisse zur Struktur der Milchstraße sowie des Interstellaren Mediums unter Berücksichtigung der für freie elektrische Ladungsträger wirksamen plasmaphysikalischen Prozesse unter dem Einfluss magnetischer Felder. Er gehörte zu den ersten, die davon ausgingen, dass die Sterne selbst aus interstellarem Material entstehen, dass Gezeitenschocks und einsetzende Gravitationsinstabilität für den schnellen Runaway-Kollaps verdichteter Molekülwolken sorgen würden. Er erforschte, wie die vermessbare Polarisation von Sternenlicht aufgrund selektiver Auslöschung durch nichtsphärische, im interstellaren Magnetfeld ausgerichtete Staubpartikel erfolgen kann (siehe **Bild 14a**). Ihm waren damals die Arbeiten von *Nicola Fermi* (1901–1954) bekannt, dem Wissenschaftler, der magnetische Prozesse für die Beschleunigung der geladenen Partikel der Kosmischen Strahlung verantwortlich machte, und der zusammen mit *Subrahmanyan Chandrasekhar* (1910–1995) Gleichgewichtszustände in kosmischen Spiralstrukturen durch die Balance zwischen dem Gravitationseinfluss sowie dem thermischen, Turbulenz- und magnetischen Druck zu erklären suchte.

In einem 1956 in Zusammenarbeit mit *Leon Mestel* (1927–2017, Bild 20) veröffentlichten wegweisenden Artikel über die „Sternentstehung in magnetischen Staubwolken" untersuchte *Lyman Spitzer* die mechanische Wirkung magnetischer Felder im Rahmen von Energiebetrachtungen nach dem sogenannten Virialtheorem, die Kopplung zwischen Magnetfeldern und mehr oder weniger stark ionisierter Materie sowie die Wolkenentwicklung, insbesondere auch bei Eingefrorenheit der Magnetfelder (Bild 15). In dieser Arbeit wurde bereits die Bedeutung sogenannter nicht-idealer magnetohydrodynamischer Prozesse im Zusammenhang mit der Ohmschen Resistivität und Ambipolaren Diffusion (siehe dazu Einschub E 2 und E 3) angesprochen. Im Kontext mit der Interaktion zwischen der Rotation und den Magnetfeldern wurde die für einen erfolgreichen Kollaps einer Staub- und Molekülwolke notwendige Abfuhr des Drehimpulses und in diesem Zusammenhang auch die Möglichkeit und Bedeutung der Fragmentation solcher Wolken sowie die Ausbildung von Akkretionsscheiben diskutiert. Vor dem Einsatz leistungsfähiger Computer konzentrierten sich Wissenschaftler damals allein auf die analytische Modellierung unter vereinfachten Annahmen in Form rein algebraischer Rechnungen, um die grundlegenden physikalischen Prozessabläufe erst einmal tiefer zu verstehen. Natürlich überprüften sie dabei die Relevanz ihrer Ergebnisse auch durch den Vergleich mit damals aktuellen Beobachtungsergebnissen, später auch mit Ergebnissen analytischer Modellrechnungen, die Wissenschaftler mit Hilfe von Computern gewonnen hatten. ([23], [24])

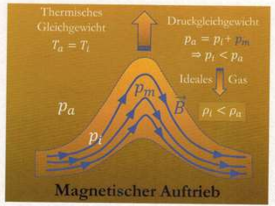


23 Dynamoprozesse zur Erzeugung von Magnetfeldern in protostellaren Systemen: Charakteristischer (blau kodierter) Feldlinienverlauf starker Magnetfelder ($\vec{B}_*$) des Protosterns sowie (rot kodierter) poloidaler ($\vec{B}_{Ap}$) bzw. (grün kodierter) toroidaler ($\vec{B}_{Ar}$) Magnetfelder im sternnahen Bereich der Akkretionsscheibe, in dessen inneren sogenannte „Todeszonen" mit extrem schwachen Magnetfeldstärken ($|\vec{B}_A| \approx 0G$) existieren können (**a**), mögliche Induktionseffekte zur Erzeugung unterschiedlicher Magnetfeldkomponenten in sogenannten *αω*-Dynamomodellen (**b**), Ergebnisse von Modellrechnungen zur zeitlichen Entwicklung (t_i, i = 1, 2, 3) toroidaler ($\vec{B}_{Ar}$) und poloidaler ($\vec{B}_{Ap}$) Magnetfeldstrukturen in Akkretionsscheiben (**c**). *U. v. Kusserow, S. Sanchez/A. Fournier/J. Aubert, U. Torkelsson/A. Brandenburg*

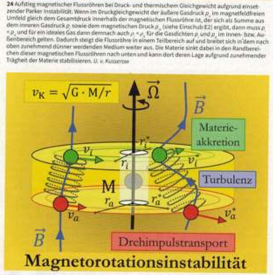
Vor allem seine vielfältigen Forschungsarbeiten über den kosmischen Magnetismus machten den primär mathematisch geschulten Theoretiker *Leon Mestel* sehr bekannt. Einer seiner fortlaufenden Interessenschwerpunkte betraf die Frage nach dem Ursprung der magnetischen Felder in Sternen. Ob sie als fossile Überreste beim Sternentstehungsprozess einfach nur verdichtet und verstärkt werden, oder ob sie als Resultat von Dynamoprozessen induziert und regeneriert werden. Sehr früh in seiner Karriere erforschte er das Problem der Sternentstehung im Interstellaren Medium, die Effekte magnetischer Felder auf kontrahierende Gaswolken. Eines seiner Schlüsselprojekte war die Untersuchung des Einflusses dieser Felder auf den Drehimpulstransport, der für die Massenzunahme des sich ausbildenden prästellaren Kerns und später des Protosterns im Zentrum einer Molekül- und Staubwolke, für die Materieakkretion in der Scheibe sowie die Ausbildung von Protoplaneten darin von zentraler Bedeutung ist [25]. Er erkannte sehr früh, dass das Prinzip der Eingefrorenheit magnetischer Feldlinien aufgrund des meist sehr geringen Ionisationsgrades der Wolkenmaterie generell nicht zutreffend sein kann.

Bei anfänglich extrem geringer Materiedichte könnten eingefrorene homogene Magnetfelder aufgrund des von ihnen ausgeübten magnetisches Drucks und ihrer magnetischen Spannung zwar die Verdichtung der Materie und damit auch die Sternentstehung behindern. Wenn die Materieverdichtung allerdings fortschreitet, der prästellare Kern mit einem sich im Kernbereich verstärkenden magnetischen Fluss weiter kontrahiert, aufgrund der Drehimpulserhaltung (siehe Text zu **Bild 2**) dadurch zunehmend schneller rotiert, dann würden in die umgebende Gaswolke eingefrorene Feldlinien die Rotation des Kernbereichs allzu stark abbremsen können. Eine solche, als „Abbremsungskatastrophe" bezeichnete Entwicklung würde aufgrund allzu schwacher Zentrifugalkräfte verhindern, dass sich protostellare Akkretionsscheiben und darin später auch Planeten überhaupt ausbilden können, was in der Realität ja nicht der Fall ist. Da sich der Ionisationsgrad der Materie in stark verdichteter Materie aufgrund dort fehlender wirksamer Ionisationsprozesse sehr stark verringert, können die Magnetfelder hierbei nicht als eingefroren betrachtet werden. Nach den theoretischen Erkenntnissen von *Leon Mestel* sorgt Ambipolare Diffusion dafür, dass neutrale Materie, die zwar immer wieder auch Stoßprozesse mit geladenen, mehr oder weniger stark an das Magnetfeld gekoppelten Partikeln erfährt, durch die Magnetfelder hindurchschlüpfen und sich dadurch im Zentralbereich zunehmend verdichten kann (siehe Einschub E2). Dabei bleiben die Magnetfelder zurück, so dass der magnetische Fluss im Innern relativ deutlich verringert bleibt.

Auch der mit mathematischen Berechnungen sehr vertraute *Frank Shu* (1943–2023, Bild 20) gehörte zu den theoretischen Astrophysikern, die in ihrem Leben bahnbrechende Beiträge zur Entstehung der Sterne sowie der Planeten im Interstellaren Medium lieferten ([26] [27]). Er entwickelte die Spiraldichtewellentheorie und wandte sie u. a. auf protoplanetare Scheiben an. Er war erstaunt über die Tatsache, dass Sterne bevorzugt entlang galaktischer Spiralarme entstehen und entwickelte daraufhin fortgeschrittene theoretische Modelle zum gravitativen Kollaps der Molekülwolken. Angeregt durch *Telemachos Mouschovias* (**Bild 20**) unterstellte er 1987 den deutlichen Einfluss magnetischer Felder in den Molekülwolken und bei der Entwicklung junger Sterne. Ein Jahr später entwickelte er im Rahmen seines sogenannten X-Windmodells einen Beschleunigungsmechanismus, der die starken protostellare Winde im Grenzbereich zwischen dem inneren Rand der Akkretionsscheiben und den Magnetosphären der Protosterne treiben könnte. Er erklärte u. a. auch den möglichen Materietransport von der Akkretionsscheibe zur Oberfläche der Protosterne entlang magnetosphärischer, die Materie trichterförmig lenkender Felder. Wie er führte auch *Mouschovias*, anfangs unterstützt auch durch Lyman Spitzer, umfangreiche Simulationsrechnungen durch. Dieser untersuchte die dynamische Rolle magnetischer Felder im interstellaren Gas, die selbstgravitative Kontraktion magnetisierter Wolken, die Rolle der magnetischen Bremsung im Zusammenhang mit dem Drehimpulstransportproblem sowie die Bedeutung der Ambipolaren Diffusion im Verhältnis zur Turbulenz bei der Entstehung von Protosternen und Akkretionsscheiben [28].



24 Aufstieg magnetischer Flussröhren bei Druck- und thermischem Gleichgewicht aufgrund einsetzender Parker Instabilität. Wenn im Druckgleichgewicht der äußere Gasdruck p_a im magnetfeldfreien Umfeld gleich dem Gesamtdruck innerhalb der magnetischen Flussröhre ist, der sich als Summe aus dem inneren Gasdruck p_i sowie dem magnetischen Druck p_m (siehe Einschub E2) ergibt, dann muss $p_i < p_a$ und für ein ideales Gas dann demnach auch $\rho_i < \rho_a$ für die Gasdichten ρ_i und ρ_a im Innen- bzw. Außenbereich gelten. Dadurch steigt die Flussröhre in einem Teilbereich auf und breitet sich in dem nach oben zunehmend dünner werdenden Medium weiter aus. Die Materie sinkt dabei in den Randbereichen dieser magnetischen Flussröhren nach unten und kann dort deren Lage aufgrund zunehmender Trägheit der Materie stabilisieren. *U. v. Kusserow*



25 Veranschaulichung der Wirkungsweise der Magnetorotationsinstabilität, die den Drehimpulstransport sowie die Materieakkretion, die Erzeugung von Turbulenzen und möglicherweise dadurch auch Dynamoprozesse in differenziell rotierenden, elektrisch leitfähigen Akkretionsscheiben ermöglicht, die von nicht allzu starken großskaligen Magnetfeldern durchsetzt sind. *U. v. Kusserow*

Basierend auf theoretischen Überlegungen, Modellierungen und Simulationsrechnungen sowie beeindruckenden Beobachtungsergebnissen entwickeln sich junge sonnenähnliche Sternsysteme nach heutigen Erkenntnissen der Astrophysiker auf sehr unterschiedlichen Raum- und Zeitskalen aufeinanderfolgend in mehreren charakteristischen Phasen (**Bild 21**).

Bei sogenannten Klasse-0-Objekten (**Bild 21**, oben) hat sich im Zentralbereich einer verdichteten Molekülwolke ein vollständig verhüllter prästellarer Kern mit umgebender Pseudoscheibe ausgebildet. Die mit dem Very Large Telescope gemachte Infrarotaufnahme des Herbig-Haro-Objekts HH 212 zeigt beidseitig, stark gebündelt aus dem Zentralbereich nahe eines prästellaren Kerns jetartig ausströmende Winde, die den Wolkenkern durchdringen können und weiter außen leuchtende Schockfronten im Interstellaren Medium erzeugen. Nach etwa 30.000 Jahren hat sich bei Klasse-I-Objekten (mittig) ein, von außen noch nicht direkt sichtbarer Protostern mit einer ihn umgebenden rotierenden Akkretionsscheibe gebildet, von der zusätzlich zu den gebündelten bipolaren Materiejets verstärkt auch weiträumig kegelförmig aufgespannte Scheibenwinde abströmen. Die nebenstehende optische und infrarote Abbildung des Hubble-Weltraumteleskops zeigt passend dazu die charakteristischen Strukturen des Herbig-Haro-Objekts HH 111. Hunderttausende Jahre später können T-Tauri-Sterne (Klasse II, unten) nach Ausdünnung der umgebenden Wolkenstrukturen bereits sichtbar werden. Wie in der nebenstehenden Hubble-Weltraum teleskop-Aufnahme des HH 32 zu erkennen ist, können diese die Scheibenstrukturen, in denen vermutlich bereits erste präplanetare Objekte entstanden sind, aufgrund starker Leuchtkraft sogar überstrahlen. Die turbulenten Winde strömen stark aufgefächert aus und erzeugen eher diffusere Schockfronten im umgebenden Interstellaren Medium. Vermutlich etwa eine Million Jahre nach Beginn der Verdichtung der Molekül- und Staubwolken entstehen darin schließlich Vorhauptreihensterne der sogenannten Klasse III, die von einer Scheibe, bestehend im Wesentlichen aus Felstrümmern und jungen Planeten, umlaufen werden. ([29], [30])

Über die Einflussnahme magnetischer Felder auf die physikalischen Prozesse in den Akkretionsscheiben, Jets und Scheibenwinden hat unter anderem Henk Spruit (Bild 20) wertvolle theoretische Beiträge geliefert [31]. *Mathew R. Bate* (Bild 20) hat mit seinen Kollegen umfangreiche Modellrechnungen zur Bedeutung magnetischer Felder für die frühe Entwicklung in den kollabierenden Molekülwolken sowie über deren Entstehung durch Dynamoprozesse in Protosternen durchgeführt [32]. Und *Axel Brandenburg* (Bild 20) analysierte mit seinen Mitarbeitern die Rolle von Turbulenzen und mögliche Dynamoprozesse in protostellaren Akkretionsscheiben im Rahmen numerischer Simulationen (**Bild 23 c**, [33]).

Die Wissenschaftler versuchen die frühe Entstehungsgeschichte unseres Sonnensystems dadurch besser zu verstehen, dass sie die physikalischen und chemischen Prozesse in jungen sonnenähnlichen Sternsystemen in diesen zeitlich aufeinanderfolgenden unterschiedlichen Entwicklungsphasen analysieren. Dabei gibt es leider wesentliche Gründe, die die wissenschaftliche Erkenntnisgewinnung stark behindern. Es gibt nicht genügend geeignete Himmelsobjekte in der Nähe der Sonne. Die räumliche Auflösung der Teleskope wird in Zukunft auch in den nächstgelegenen protostellaren Systemen nicht ausreichen, um dort Abmessungen kleiner als eine Astronomische Einheit detailliert beobachten zu können. Nach heutigen Erkenntnissen werden die Astrophysiker vermutlich niemals genügend sonnenähnliche Protosterne in unterschiedlichen Entwicklungsstufen finden, bei der die Struktur der sie umgebenden Planetensysteme dem unsrigen wirklich ähnlich ist. Im Rahmen hochauflösender numerischer Simulationsrechnungen lassen sich zwar heute schon Strukturen von Abmessungen der Größe 0,1 AE analysieren. Sowohl der Rechenzeit- als auch Kostenaufwand dafür kann allerdings sehr hoch sein. Numerisch bedingte Fehler können die Aussagekraft der erzielten Ergebnisse außerdem verfälschen. Schließlich fallen die Interpretation, die verlässliche Einschätzungen der detaillierten Wirksamkeiten und komplexen Zusammenhänge zugrundeliegender physikalischer und chemischer Prozesse in solchen komplexen und nichtlinearen Simulationsrechnungen unter Umständen sehr schwer.

Genaue, hochaufgelöste Messungen der Stärke, Ausrichtung und Orientierung magnetischer Felder, die anerkannterweise eine wichtige Rolle bei Strukturbildungs- und Entwicklungsprozessen protostellarer Systeme spielen, erweisen sich vor allem aufgrund der großen Entfernung der Himmelsobjekte von der Erde als sehr schwierig. Hier bieten eher Modell- und Simulationsrechnungen die Möglichkeit tieferer Erkenntnisgewinnung über die Hintergründe des magnetisch vermittelten Transports von Materie, Drehimpuls sowie des Magnetflusses in sonnenähnlichen Protosternsystemen.

E3 Magnetfelderzeugungsprozesse in Protostellaren Systemen

Nach dem sogenannten Biermann-Batterie-Effekt können in elexktrisch, leitfähigen, dünnen Medien zeitliche Variationen $\partial\vec{B}/\partial t$, also auch Verstärkungen der magnetischen Flussdichte $\vec{B}$ gemäß der theoretisch herleitbaren Beziehung

$$\frac{\partial\vec{B}}{\partial t} = \frac{m_p}{2e} \cdot \frac{\vec{\nabla}\rho \times \vec{\nabla} p}{\rho^2} \quad (1)$$

ohne vorherige Existenz eines magnetischen Saatfeldes (kein $\vec{B}$ auf der rechten Seite dieser Differenzialgleichung!) genau dort erfolgen, wo die Druck- ($\vec{\nabla}p$) und Dichtegradienten ($\vec{\nabla}\rho$) nicht parallel verlaufen, für das vektorielle Kreuzprodukt also $\vec{\nabla}\rho \times \vec{\nabla}p \neq \vec{0}$ gilt. m_p bezeichnet in dieser Gleichung die Masse des am häufigsten anzutreffenden Wasserstoffatoms, *e* die Elementarladung.

Die häufiger im Rahmen einfacher kinematischer (ohne Berücksichtigung von Rückkopplungsprozessen der erzeugten Magnetfelder auf die strömende, elektrisch leitfähige Materie) *αω*-Dynamomodelle verwendete Differenzialgleichung

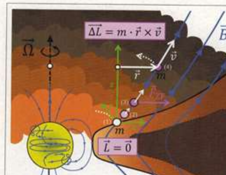
$$\frac{\partial\vec{B}}{\partial t} = \underbrace{\vec{\nabla}\times\vec{v}\times\vec{B}}_{\omega\text{-Effekt}} + \underbrace{\vec{\nabla}\times(\alpha\cdot\vec{B})}_{\alpha\text{-Effekt}} + \underbrace{\eta\cdot\vec{\nabla}^2\vec{B}}_{\text{Diffusionsterm}} \quad (2)$$

beschreibt mathematisch, wie die *α*- und *ω*-Induktionseffekte für die zeitliche Generierung, ein zusätzlicher Diffusionsterm bei Ohmscher Resistivität oder durch magnetische Rekonnexion für den Abbau bzw. drastische Topologieänderungen des Magnetfeldes sorgen kann. $\vec{v}$ bezeichnet die Geschwindigkeit des elektrisch leitfähigen Mediums. Die Magnetische Diffusivität $\eta = 1/(\mu_0 \cdot \sigma)$ ist umgekehrt proportional zur elektrischen Leitfähigkeit σ und zur magnetischen Permeabilitätskonstanten μ_0. [35][36]

Betrachtet man die mit der Geschwindigkeit $\vec{v}$ strömende und Magnetfelder der Flussdichte $\vec{B}$ induzierende teilionisierte Materie nicht als quasi-neutral, sondern berücksichtigt man darin separat sowohl die Teilchenbewegung der negativ geladenen Elektronen als auch die der positiv geladenen Protonen, so lässt sich nach umfangreichen analytischen Betrachtungen gemäß

$$\frac{\partial\vec{B}}{\partial t} = \left[\vec{\nabla}\times\vec{v}\times\vec{B} - \eta_{OR}\,\vec{\nabla}\times\vec{B} - \eta_{HE}\,(\vec{\nabla}\times B)\times\vec{B} - \eta_{AD}\,((\vec{\nabla}\times\vec{B})\times\vec{B})\right] \quad (3)$$

eine wesentlich komplexere, sogenannte nicht-ideale MHD-Induktionsgleichung herleiten [35]. Neben dem üblichen ersten Induktionsterm auf der rechten Seite der Gleichung, der für die Erzeugung der Magnetfelder verantwortlich ist, bestimmen darin je nach Eigenschaft der Materie drei unterschiedlich wichtige Diffusionsterme die zeitliche und räumliche magnetische Entwicklung detaillierter. η_{OR}, η_{HE} und η_{AD} bezeichnen darin jeweils Koeffizienten, die den unterschiedlichen Einfluss der Ohmschen Resistivität (OR), des Hall-Effekts (HE) sowie der Ambipolaren Diffusion (AD) charakterisieren (siehe dazu auch Einschub E2).

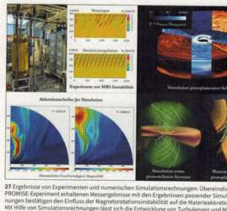


26 Veranschaulichung der Wirkungsweise des Drehimpulstransportes in rotierenden protostellaren Akkretionsscheiben durch zentrifugal getriebene Winde entlang genügend stark geneigter poloidaler magnetischer Scheibenfelder. Die Angaben zum Drehimpulsvektor $\vec{L}$ beziehen sich auf ein dort mit der Akkretionsscheibe mitrotierendes Koordinatensystem (*x, y, z*), wo die ganz links eingezeichnete Feldlinie des magnetischen Feldes $\vec{B}$ aus der Scheibe austritt. *U. v. Kusserow*

Magnetfluss-, Drehimpuls- und Materietransport in sonnenähnlichen Protosternsystemen

Die großskaligen Magnetfeldstrukturen, die sich verstärkt parallel zu den Spiralarmen von Galaxien, (erst vor kurzem definitiv nachgewiesen) auch unserer Milchstraße ausrichten, werden in sogenannten *αω*-Dynamoprozessen (siehe **Bild 23 b**) erzeugt. Bild 22 veranschaulicht die charakteristische Ausrichtung der Magnetfelder in den Spiralarmen der vom Kitt Peak Observatory aufgenommenen Galaxie IC 342, die durch Polarisationsmessungen mit Hilfe des VLA (Bild 19c) sowie des Radiotelekops in Effelsberg ermittelt wurde. Sie bestimmt dabei auch die Vorzugsausrichtung der magnetischen Felder in den sich jeweils lokal verdichtenden Molekül- und Staubwolken, in denen sich die jungen protostellaren Sternsysteme ausbilden. Als Saatfelder in geeignet turbulent verwirbelten Teilbereichen können diese Magnetfelder die Regeneration zusätzlicher kleinskaliger Magnetfelder in sogenannten turbulenten Dynamoprozessen unterstützen. Dort, wo zum Beispiel aufeinandertreffende Schockfronten für eine vorübergehend nichtparallele Ausrichtung der Gradienten $\vec{\nabla}p$ und $\vec{\nabla}\rho$ des Gasdruckes und der Materiedichte im verdichteten Interstellaren Medium sorgen, können darüber hinaus Magnetfelder lokal sogar auch ohne vorherige Existenz magnetischer Saatfelder aufgrund des 1950 von *Ludwig Biermann* (1907–1986) entdeckten und nach ihm benannten Batterie-Effekts generiert werden (siehe **Einschub E3**). [34][35]

In jungen Protosternen werden schon recht früh, im Vergleich zur Sonne (Stärke der magnetischen Flussdichte $|\vec{B}| \approx 10$ G) um Größenordnungen stärkere (1–3 kG), zeitlich oszillierende Oberflächenmagnetfelder in Dynamoprozessen erzeugt (**Bild 23a**). Wie die Ergebnisse von Simulationsrechnungen (**Bild 23c**) zeigen, kann dies auch für die wesentlich schwächeren Oberflächenmagnetfelder (mG bis G) im inneren Bereich der Akkretionsscheiben der Fall sein (Bild 23a). **Bild 23b** veranschaulicht, wie poloidale (polwärts gerichtete) Magnetfelder und toroidale (azimutal aufgewickelte) Magnetfeldkomponenten durch den sogenannten Omega- bzw. Alpha-Effekt im Laufe der zeitlichen Entwicklung von Aktivitätszyklen wechselseitig ineinander umgewandelt werden können (siehe Einschub E3). Der *ω*-Effekt bewirkt die azimutale Aufwicklung poloidaler Felder zu toroidalen Feldern unter Einfluss differenzieller Rotation in elektrisch extrem gut leitender und daher wie eingefroren an die Magnetfelder eng gekoppelter Materie. Nach dem als klassisch bezeichneten *α*-Effekt können Konvektionsströmungen unter Einfluss der Corioliskraft für die helikale Verformung toroidaler Felder im Innern eines elektrisch weitgehend widerstandsfreien Mediums und damit für die lokale Ausbildung kleinskaliger poloidaler Felder sowie deren Überlagerungen zur Regenerierung großskaliger poloidaler Felder sorgen. Nach einem anderen, von *Horace Welcome Babcock* (1912–2003) und *Robert Benjamin Leighton* (1919–1997) in den 1960er Jahren vorgeschlagenen Mechanismus, sorgt demgegenüber magnetischer Auftrieb (**Bild 24**) für den Aufstieg toroidaler Feldstrukturen in dünnere Atmosphärenschichten, wo großskaligere Konvektionsströmungen, Scherungs- und Corioliskräfte die Ausbildung poloidaler Felder wesentlich leichter ermöglichen. Diese zyklisch mit charakteristischen Periodenlängen ablaufenden Umwandlungsprozesse werden mathematisch-physikalisch im Rahmen sogenannter *αω*-Dynamomodelle analysiert und numerisch simuliert.



27 Ergebnisse von Experimenten und numerischen Simulationsrechnungen: Übereinstimmung der am PROMISE-Experiment erhaltenen Messergebnisse mit den Ergebnissen passender Simulationsrechnungen bestätigen den Einfluss der Magnetorotationsinstabilität auf die Materieakkretion (links oben). Mit Hilfe von Simulationsrechnungen lässt sich die Entwicklung von Turbulenzen und Magnetfeldern in Akkretionsscheiben protostellarer Systeme analysieren (rechts oben). Simulationsrechnungen zeigen, wie dynamogenerierte magnetische Scheibenfelder den epochenartigen Auswurf von Scheibenwinden steuern (links unten). Die Ergebnisse von Simulationsrechnungen veranschaulichen, wie der Drehimpulsabtransport in protostellaren Scheibenwinden die Ausbildung von Protoplaneten in Akkretionsscheiben ermöglicht (rechts unten). *F. Stefani (FZDR), M. Flock (MPIA), C. Fendt (MPIA), Oliver Gressel (AIP), U. v. Kusserow*

Solange sich ihr Drehimpuls nicht ändert, keine Drehmomente von außen auf sie einwirken, umrunden die Planeten unseres Sonnensystems die Sonne bekanntlich auf weitgehend stabilen Kepler-Bahnen (siehe Text zu **Bild 2**). Der aus mehreren Gründen erforderliche Materietransport in den Akkretionsscheiben früher protostellarer Systeme kann von daher effektiv nur durch den Transport von Drehimpuls gelingen. Zunächst waren Naturforscher davon ausgegangen, dass Reibungskräfte aufgrund der Teilcheninteraktion die Materie abbremsen könnten, so dass diese langsamer auf immer näher zum Zentralbereich gelegenen Orbits in anfangs nur schwach rotierenden Wolken umlaufen würde. Da sich die Viskosität, die Zähigkeit des Gases dafür allerdings um Zehnerpotenzen als zu klein erwies, vertrauten die Wissenschaftler danach auf eine 1973 von *Nikolay Shakura* und *Rashid Sunyaev* (**Bild 20**) entwickelte Akkretionstheorie, die ursprünglich für die Akkretion in dünnen Scheiben um Schwarze Löcher aufgestellt worden war. Nach dieser Theorie, die von einer hohen Strahlungseffizienz der Scheibenmaterie ausgeht, sollen Turbulenzen und magnetisch vermittelte Viskositäten im Wesentlichen für die Übertragung von Drehimpuls verantwortlich sein. Die in dieser Theorie verwendete parametrisierte Formel $\nu_v = \alpha \cdot c_s \cdot H$ zur Berechnung der sogenannten „anomalen" Viskosität ν_v, in der c_s die Schallgeschwindigkeit und *H* etwa die charakteristische Höhe der Scheibe bezeichnen, bestimmt der jeweils geeignet zu ermittelnde sogenannte Shakura-Sunyaev Parameter *α* den Grad der turbulent vermittelten Reibung in der Materie von Akkretionsscheiben. Für *α*, welches das Verhältnis von Spannungs- zu Druckkräften im Medium angibt, werden typische Werte zwischen 0,01 und 1 angenommen, allerdings, ohne dass damals physikalische Prozesse als dafür verantwortlich gefunden worden waren.

Bereits 1959 bzw. 1961 hatten *Evgeny Pavlovich Velikhov* sowie *Subrahmanyan Chandrasekhar* einen physikalischen Mechanismus studiert, durch den der Transport von Drehimpuls in Folge einer Instabilität erfolgt, die in differenziell rotierenden Scheiben einsetzen kann, wenn diese von einem nicht allzu starken Magnetfeld axial durchsetzt sind. Erst durch die 1991 von *Steven Andrew Balbus* (Bild 20) und *John Frederick Hawley* (1958–2021) veröffentlichte Arbeit mit dem Titel „Eine starke lokale Scherinstabilität in schwach magnetisierten Scheiben", in der sie analytisch eine lineare Analyse dieser sogenannten Magnetorotationsinstabilität (MRI) für Akkretionsscheiben durchführten, erfuhr dieser Mechanismus große Aufmerksamkeit in der astrophysikalischen Forschung. In **Bild 25** wird anschaulich dargestellt, wie diese Balbus-Hawley Instabilität im Prinzip wirkt, um den Akkretionsprozess zu ermöglichen, Turbulenzen und damit auch Dynamoprozesse in Scheiben um junge Protosterne zu erzeugen (Bild 23). ([37], [38])

Betrachtet man zwei benachbarte, in diesem einfachen Bild grün bzw. rot markierte, durch eine magnetische Feldlinie verbundene Materieelemente, die durch kleinste Störungen nach innen (grün) bzw. nach außen (rot) bewegt werden, dann bewegt sich das innere Materieelement im Fall der Kepler-Bewegung aufgrund der Drehimpulserhaltung gemäß $v_K(r) = \sqrt{G\cdot M/r}$ mit einer größeren Geschwindigkeit v_i als das äußere Materieelement mit der Geschwindigkeit v_a. Analog zu einer gespannten Federspirale zwingt die Spannung in der magnetischen Feldlinie das innere Materieelement zu einer Verlangsamung, so dass es weiter nach innen driftet. Das äußere Materieelement wird demgegenüber durch die magnetische Kopplung beschleunigt und driftet weiter nach außen. Da beide Elemente zunehmend weiter auseinanderdriften anstatt sich wieder aufeinander zuzubewegen, sorgt dieses instabile Verhalten für Turbulenzen in Akkretionsscheiben. Materie des inneren Materieelements wird dabei nach innen transportiert, Drehimpuls mit dem äußeren Materieelement nach außen abgeführt. [39]

Drehimpuls kann in protostellaren Systemen aufgrund von Reibungsprozessen auch dort abtransportiert werden, wo im Grenzbereich zwischen dem sich verdichtenden prästellaren Kern und der sich ausbildenden Akkretionsscheibe intensive Scherströmungen aufgrund starker Gradienten in der Winkelgeschwindigkeit wirksam werden. Bei der Wechselwirkung zwischen magnetosphärischen Feldern junger Protosterne und poloidalen magnetischen Feldkomponenten im Bereich des inneren Randes der Akkretionsscheibe können zudem auch magnetische Rekonnexionsprozesse (**Bild 15**) für die Beschleunigung und den Auswurf von Plasmamaterie und Drehimpuls aus dem protostellaren System sorgen. Dabei sich verdrillende Magnetfelder regen die Ausbreitung magnetohydrodynamischer Alfvén-Wellen an, die *Hannes Alfvén* (**Bild 6**) schon 1943 für den möglichen Transport von Drehimpuls verantwortlich gemacht hatte. 1966 waren es *Edmund J. Weber* und *Leverett Davis*, die, auch in diesem Zusammenhang von einigem Interesse, erstmals ein leistungsfähiges analytisches Modell für den effektiven Fluss von Drehimpuls speziell im magnetischen Sonnenwind entwickelten.

In ihrer grundlegenden Arbeit aus dem Jahre 1982 untersuchten *Roger D. Blandford* und *David G. Payne* (**Bild 20**) anhand analytischer Modellrechnungen die Möglichkeit, dass Energie und Drehimpuls aus rotierenden Akkretionsscheiben entlang magnetischer Feldlinien, die von der Scheibenoberfläche ausgehen, bis in großen Entfernungen aus dem System hinaustransportiert werden können. **Bild 26** veranschaulicht das zugrundeliegende Prinzip, wonach der Auswurf von Plasmamaterie entlang der Feldlinien zentrifugal getrieben gelingen kann, wenn die Materiepartikel aufgrund genügend schneller Scheibenrotation (Winkelgeschwindigkeit $\vec{\Omega}$) wie Perlen entlang einer Schnur schräg nach außen geworfen werden. Dafür müssen die Feldlinien allerdings genügend stark (mehr als etwa 30°) gegenüber der vertikalen Achse des grünlich eingezeichneten Koordinatensystems geneigt sein. [40]

In diesem, mit der Scheibe mitrotierenden Koordinatensystem, besitzt das Teilchen mit der Masse *m* auf der Scheibenoberfläche anfangs noch keinen Drehimpuls ($\vec{L} = \vec{0}$). Unter dem Einfluss der Zentrifugalkraft $\vec{F}_{Zf}$ wird dieses Materieelement im rotierenden System beschleunigt und bewegt sich entlang der magnetischen Feldlinie zunehmend schneller nach außen. Es erfährt dabei einen Zuwachs $\overrightarrow{\Delta L} = m \cdot \vec{r} \times \vec{v}$ an Drehimpuls (siehe dazu auch **Bild 2b**). Aufgrund der für das Gesamtsystem geltenden Drehimpulserhaltung muss sich folglich der Drehimpuls am Fußpunkt der Magnetfeldlinie um den nach außen abgeführten Drehimpuls $\overrightarrow{\Delta L}$ verringert haben. Allerdings nur bis zu dem sogenannten Alfvén-Punkt ist die Energiedichte des magnetischen Feldes dabei stark genug im Vergleich zur kinetischen Energie der Windpartikel, so dass die poloidalen magnetischen Feldlinien (wie abgebildet) starr mit der Scheibe mitrotieren. Weiter außerhalb erzwingt die Trägheit der ausströmenden Teilchen dann jedoch die azimutale Aufwicklung der nach außen zunehmend schwächer werdenden Magnetfelder.

Neben Erkenntnissen aufgrund aktueller Beobachtungsergebnisse sowie der Fortentwicklung zugrundeliegender Theorien spielen heute vor allem die Ergebnisse zeit- und kostenaufwendiger numerischer Simulationen, inzwischen auch Erkenntnisse aus Laborexperimenten insbesondere auch über den Einfluss magnetischer Prozesse auf die Sternentwicklung und Planetenentstehung eine zentrale Rolle. **Bild 27** oben links zeigt den Aufbau eines Experiments zum Einfluss der Magnetorotationsinstabilität auf den Drehimpulstransport, das am Forschungszentrum Dresden-Rossendorf (FZDR) von einer Gruppe um *Frank Stefani* [41] durchgeführt wurde. Im rechten Teil dieser Abbildung sind die weitgehend übereinstimmenden Ergebnisse von Messungen sowie Simulationsrechnungen der sich zeitlich systematisch entwickelnden Geschwindigkeitsgrößen im Innern farbkodiert dargestellt, die den Transport von Materie aufgrund einsetzender Magnetorotationsinstabilität dokumentieren. Bild 27 oben rechts zeigt die Ergebnisse von Simulationsrechnungen zur zeitlichen und räumlichen Entwicklung magnetischer Turbulenzen in Akkretionsscheiben, die vom Team um *Mario Flock* [42] am Max-Planck-Institut für Astronomie (MPIA) in Heidelberg durchgeführt wurden. *Christian Fendt* [43] und Mitarbeiter am MPIA haben in ihren Simulationsrechnungen die zeitliche Entwicklung jetartiger magnetischer Scheibenwinde untersucht (Bild 27, unten links), in denen episodisch erfolgende, knotenartig sichtbare Materieauswürfe, angeregt durch oszillierende Dynamoprozesse im protosternnahen Bereich der Akkretionsscheibe, stattfinden.

Auch *Oliver Gressel* [44] vom Leibniz-Institut für Astrophysik Potsdam (AIP) führt Simulationsrechnungen zur Analyse der Vorgänge in magnetisierten protostellaren Systemen sowie der Entstehung junger Protoplaneten in den Akkretionsscheiben durch (Bild 27, unten rechts). Der rechte Teil dieser Abbildung, in der die Verteilung der Gasdichte, die Strömungslinien der Materie gelblich und die Magnetfeldlinien weißlich visualisiert sind, veranschaulicht, wie ein junger Planet eine Spaltöffnung in der Akkretionsscheibe erzeugt.

Wie und wo die Planeten und Monde in den Akkretionsscheiben sonnenähnlicher Protosternsysteme innerhalb der Molekül- und Staubwolken aus Staub-, Gas- und Eispartikeln insbesondere auch unter Einfluss magnetischer Felder entstehen können, darum wird es im letzten Teil dieser Artikelserie gehen. Besonderes Augenmerk soll dabei konkret auch auf Modelle zur Strukturbildung und frühen Entwicklung unseres eigenen Sonnensystems gelegt werden. Entscheidende Entwicklungsvorgänge lassen sich dabei im sogenannten Hertzsprung-Russell-Diagramm speziell für die Sonne überblickartig verfolgen.

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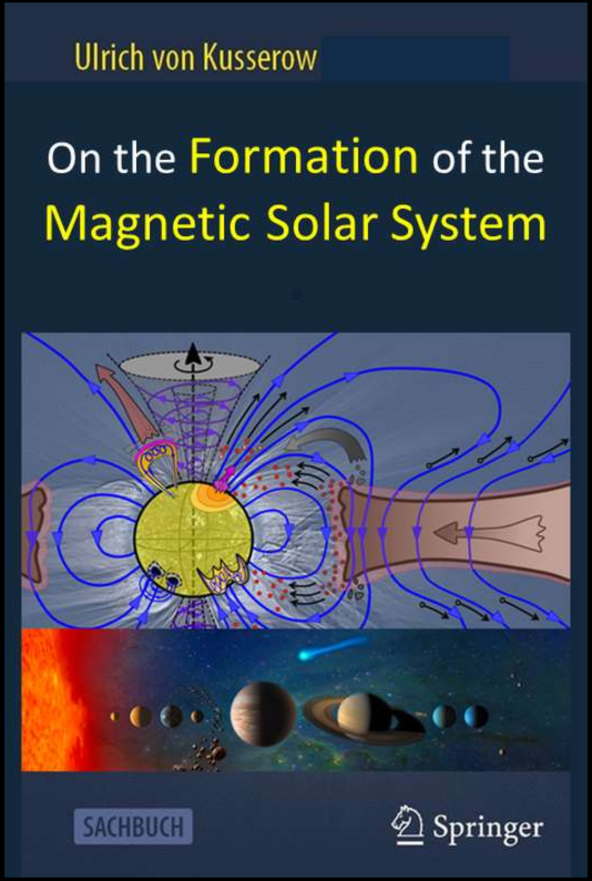

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Protostars and Planets VII

Participants "Protostars and Planets VII“, 2023 Kyoto

19th MHD Days 2024

2–4 Dec 2024
Leibniz Institute for Astrophysics Potsdam (AIP)

Mo. 02/12

14:00

Opening *Oliver Gressel*
Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 14:00 - 14:10

Interplays between dynamo and magneto-rotational instabilities *Axel Brandenburg*
Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 14:10 - 14:50

Sunspot simulations with potential field initial conditions *Markus Schmassmann*

15:00

Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 14:50 - 15:10

Solar magnetic tornadoes ignite ambient shock waves: The surprising story of how torsional Alfvén waves can dissipate
Oskar Steiner

Break
Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 15:30 - 16:00

16:00

Harmonically forced and synchronized dynamos *Frank Stefani*
Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 16:00 - 16:20

Orbit-Spin Coupling and Variations in the Length of the Hale Cycle *James Shirley*
Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 16:20 - 16:40

Deep cyclic magnetic activity of the Sun by assimilating long-term observed photospheric magnetograms in a 3D dyna…
Gopal Hazra

17:00

Evaluating solar-like behavior in extra-long non-kinematic flux-transport solar dynamos *Fadil Inceoglu*
Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 17:00 - 17:20

Di. 03/12

09:00

Magnetic Fields and Cosmic Ray Electrons (CREs) in Halos of Star Forming Disk Galaxies *Ralf-Juergen Dettmar*
Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 09:00 - 09:20

Zooming-in on radio relics: How density fluctuations explain the Mach number discrepancy, microgauss magnetic field…
Joseph Whititngham

Cosmic magnetic fields: A new window to the fundamental physics of the early Universe *Jennifer Schober*
Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 09:40 - 10:00

10:00

Early magnetic field growth in galaxy clusters; the crucial contribution from galaxy formation physics *Larissa Tevlin*
Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 10:00 - 10:20

Turbulent plasma flow, its energies and structures: velocity vortices, magnetic field cocoons and plasmoids *Petr Jelínek*
Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 10:20 - 10:40

Break
Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 10:40 - 11:00

11:00

Tayler Instability Revisited *Valentin Skoutnev*
Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 11:00 - 11:20

Stability of toroidal magnetic fields in radiative stellar interiors *Giovanni Licciardello*
Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 11:20 - 11:40

Stability of toroidal magnetic fields in radiative stellar interiors: insights from direct numerical simulations and stellar e…
Domenico G. Meduri

12:00

MHD and the Formation of the Magnetic Solar System - A didactically oriented approach *Ulrich von Kusserow*
Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 12:00 - 12:20

Group photo
Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP) 12:20 - 12:30

19th MHD Days 2024

2–4 Dec 2024
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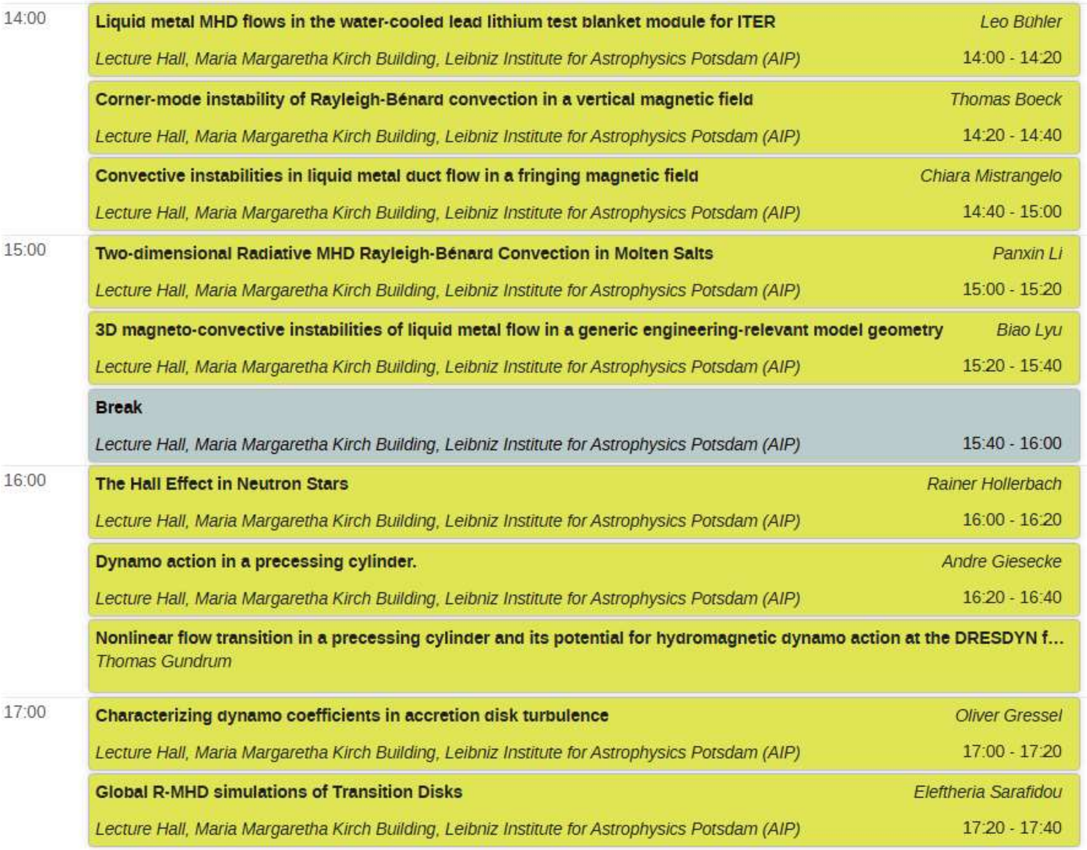
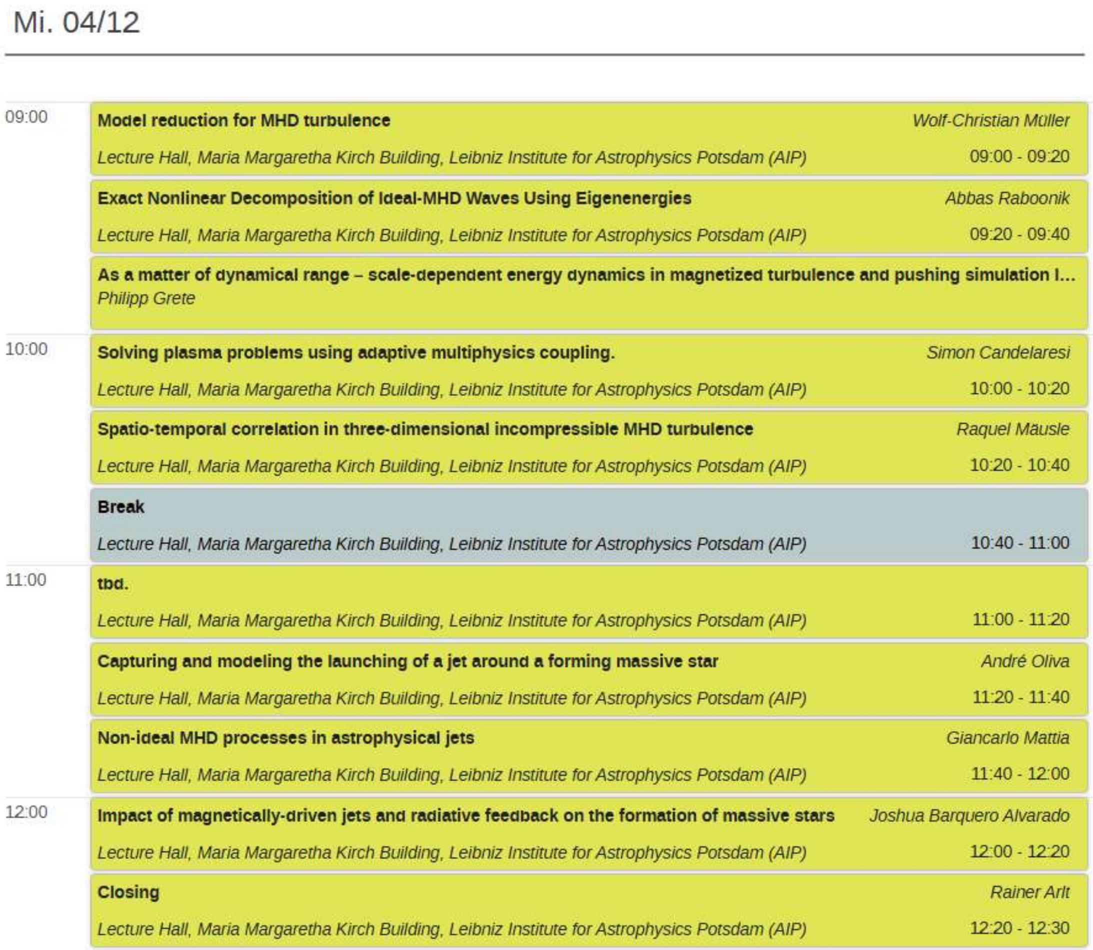
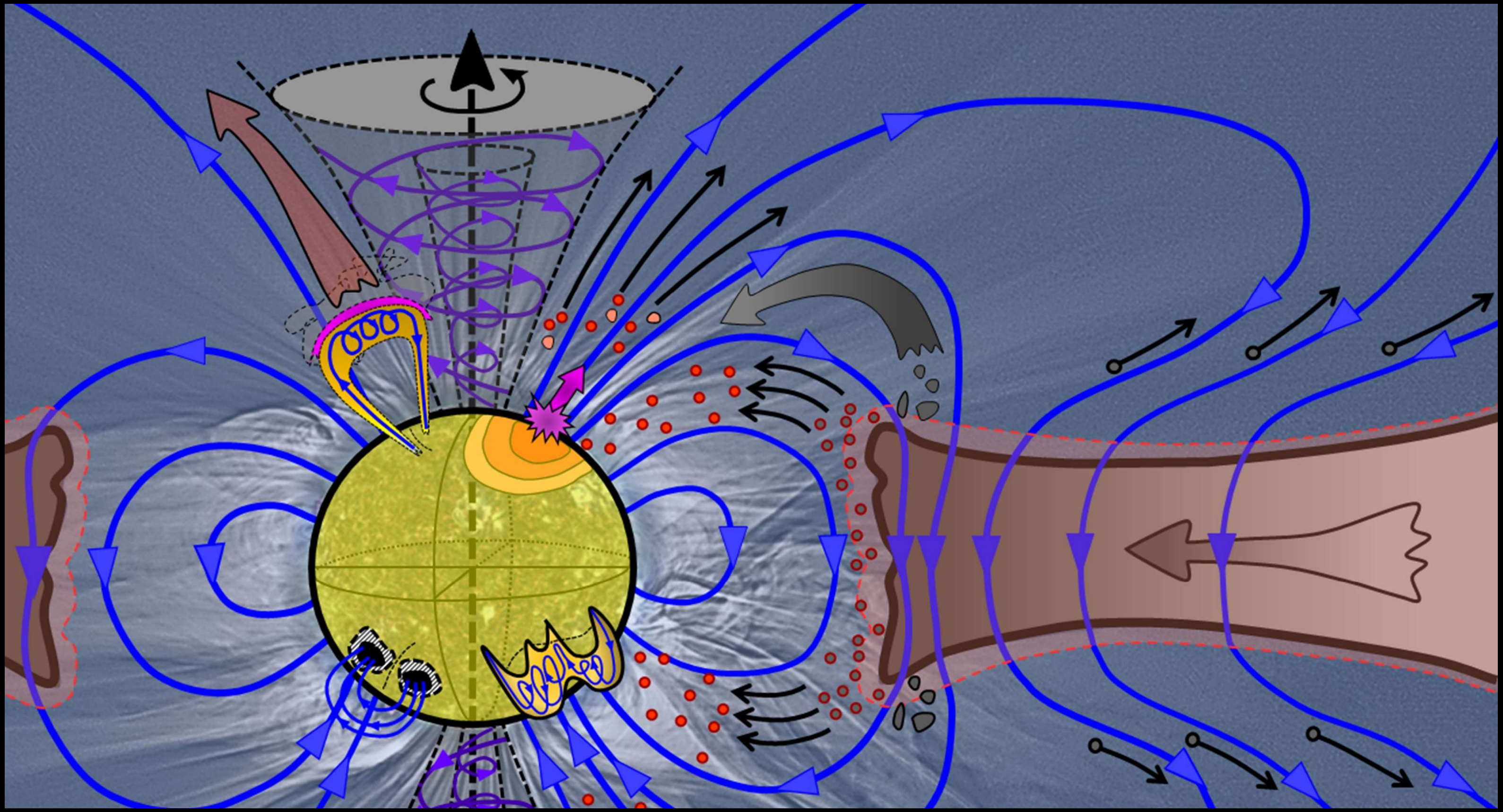


	Title	Speaker	Location	Time
14:00	**Liquid metal MHD flows in the water-cooled lead lithium test blanket module for ITER**	*Leo Bühler*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	14:00 - 14:20
	Corner-mode instability of Rayleigh-Bénard convection in a vertical magnetic field	*Thomas Boeck*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	14:20 - 14:40
	Convective instabilities in liquid metal duct flow in a fringing magnetic field	*Chiara Mistrangelo*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	14:40 - 15:00
15:00	**Two-dimensional Radiative MHD Rayleigh-Bénard Convection in Molten Salts**	*Panxin Li*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	15:00 - 15:20
	3D magneto-convective instabilities of liquid metal flow in a generic engineering-relevant model geometry	*Biao Lyu*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	15:20 - 15:40
	Break		*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	15:40 - 16:00
16:00	**The Hall Effect in Neutron Stars**	*Rainer Hollerbach*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	16:00 - 16:20
	Dynamo action in a precessing cylinder.	*Andre Giesecke*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	16:20 - 16:40
	Nonlinear flow transition in a precessing cylinder and its potential for hydromagnetic dynamo action at the DRESDYN f…	*Thomas Gundrum*		
17:00	**Characterizing dynamo coefficients in accretion disk turbulence**	*Oliver Gressel*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	17:00 - 17:20
	Global R-MHD simulations of Transition Disks	*Eleftheria Sarafidou*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	17:20 - 17:40



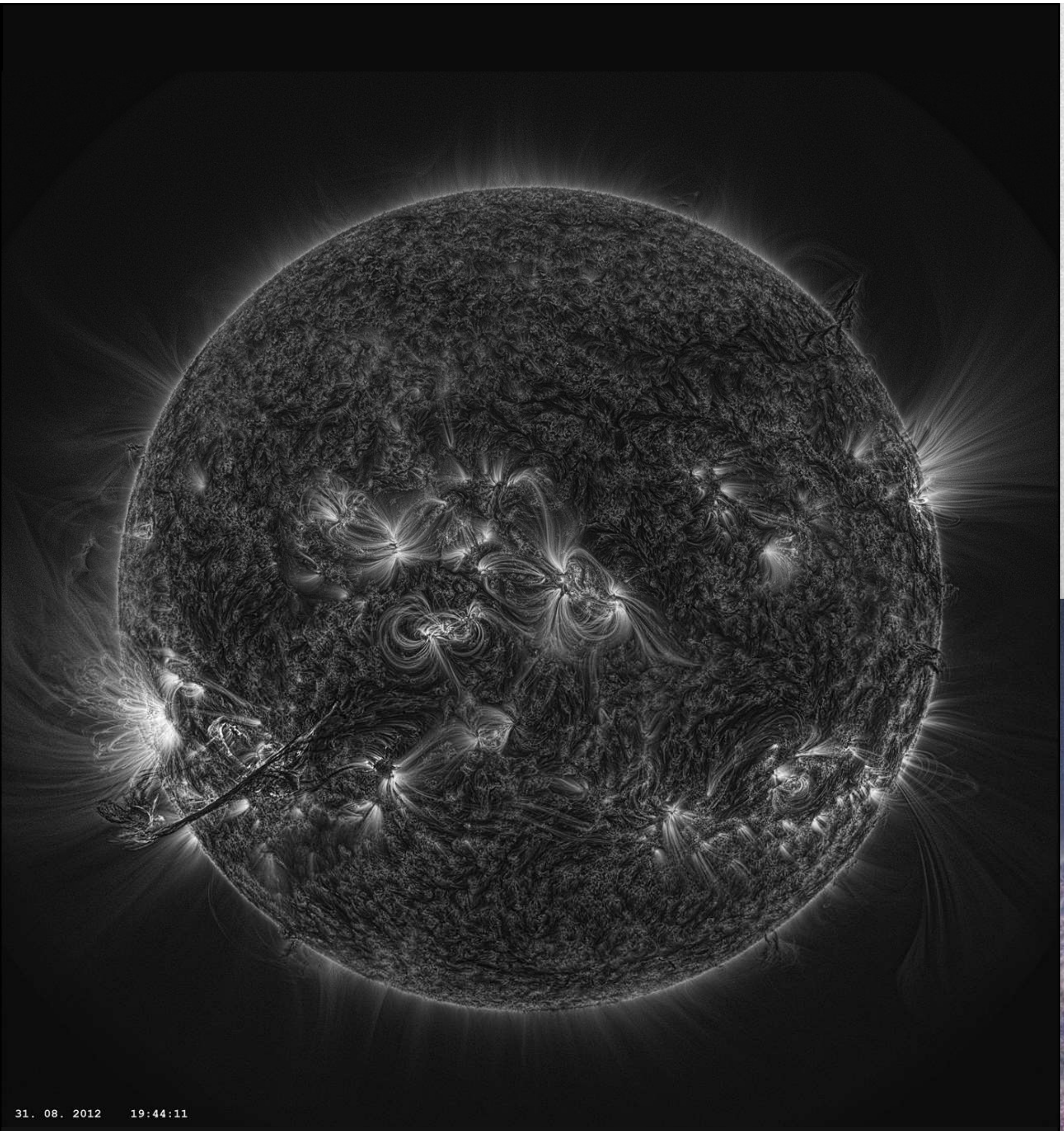
Mi. 04/12

	Title	Speaker	Location	Time
09:00	**Model reduction for MHD turbulence**	*Wolf-Christian Müller*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	09:00 - 09:20
	Exact Nonlinear Decomposition of Ideal-MHD Waves Using Eigenenergies	*Abbas Raboonik*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	09:20 - 09:40
	As a matter of dynamical range – scale-dependent energy dynamics in magnetized turbulence and pushing simulation l…	*Philipp Grete*		
10:00	**Solving plasma problems using adaptive multiphysics coupling.**	*Simon Candelaresi*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	10:00 - 10:20
	Spatio-temporal correlation in three-dimensional incompressible MHD turbulence	*Raquel Mäusle*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	10:20 - 10:40
	Break		*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	10:40 - 11:00
11:00	**tbd.**		*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	11:00 - 11:20
	Capturing and modeling the launching of a jet around a forming massive star	*André Oliva*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	11:20 - 11:40
	Non-ideal MHD processes in astrophysical jets	*Giancarlo Mattia*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	11:40 - 12:00
12:00	**Impact of magnetically-driven jets and radiative feedback on the formation of massive stars**	*Joshua Barquero Alvarado*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	12:00 - 12:20
	Closing	*Rainer Arlt*	*Lecture Hall, Maria Margaretha Kirch Building, Leibniz Institute for Astrophysics Potsdam (AIP)*	12:20 - 12:30

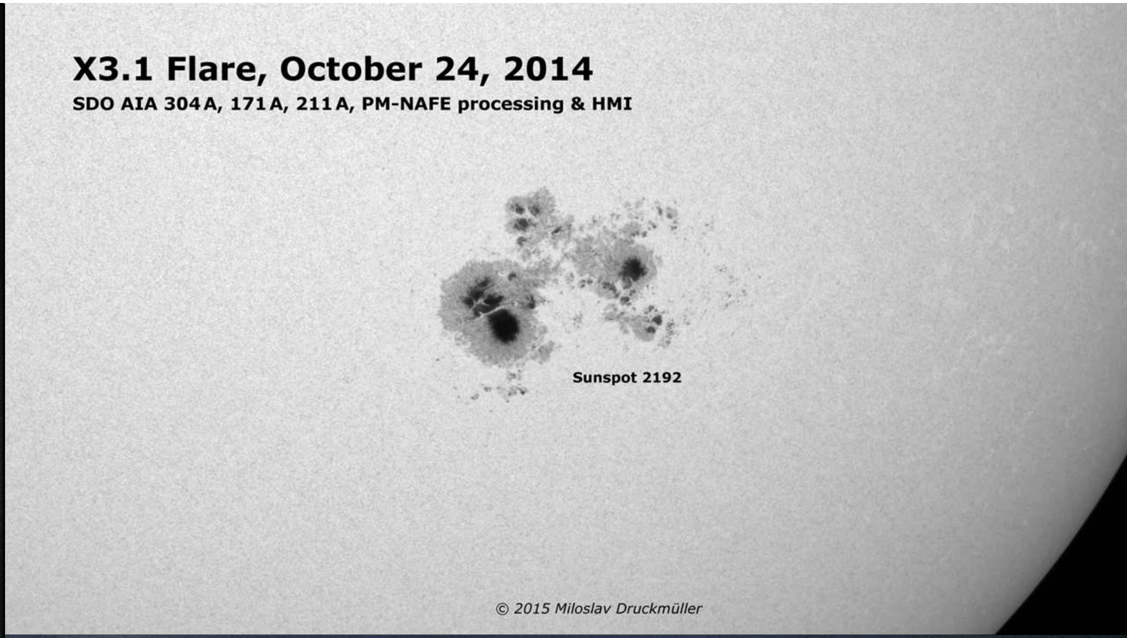


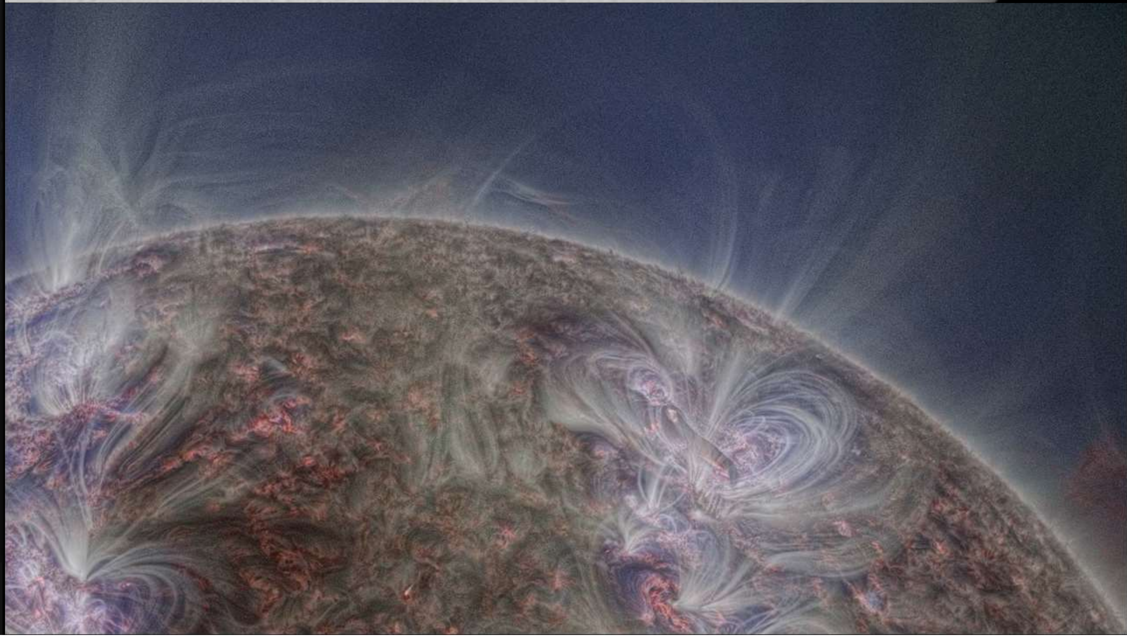
$$\frac{\partial\vec{B}}{\partial t} = \vec{\nabla}\times\left(\vec{v}\times\vec{B}\right) - \vec{\nabla}\times\left(\eta_{\mathrm{OD}}\cdot\vec{\nabla}\times\vec{B}\right) + \vec{\nabla}\times\left\{\eta_{\mathrm{AD}}\cdot(\vec{\nabla}\times\vec{B})\times\vec{B}\right\} - \vec{\nabla}\times\left[\vec{\nabla}\times\left\{\eta_{\mathrm{HD}}\cdot(\vec{\nabla}\times\vec{B})\times\vec{B}\right\}\right]$$

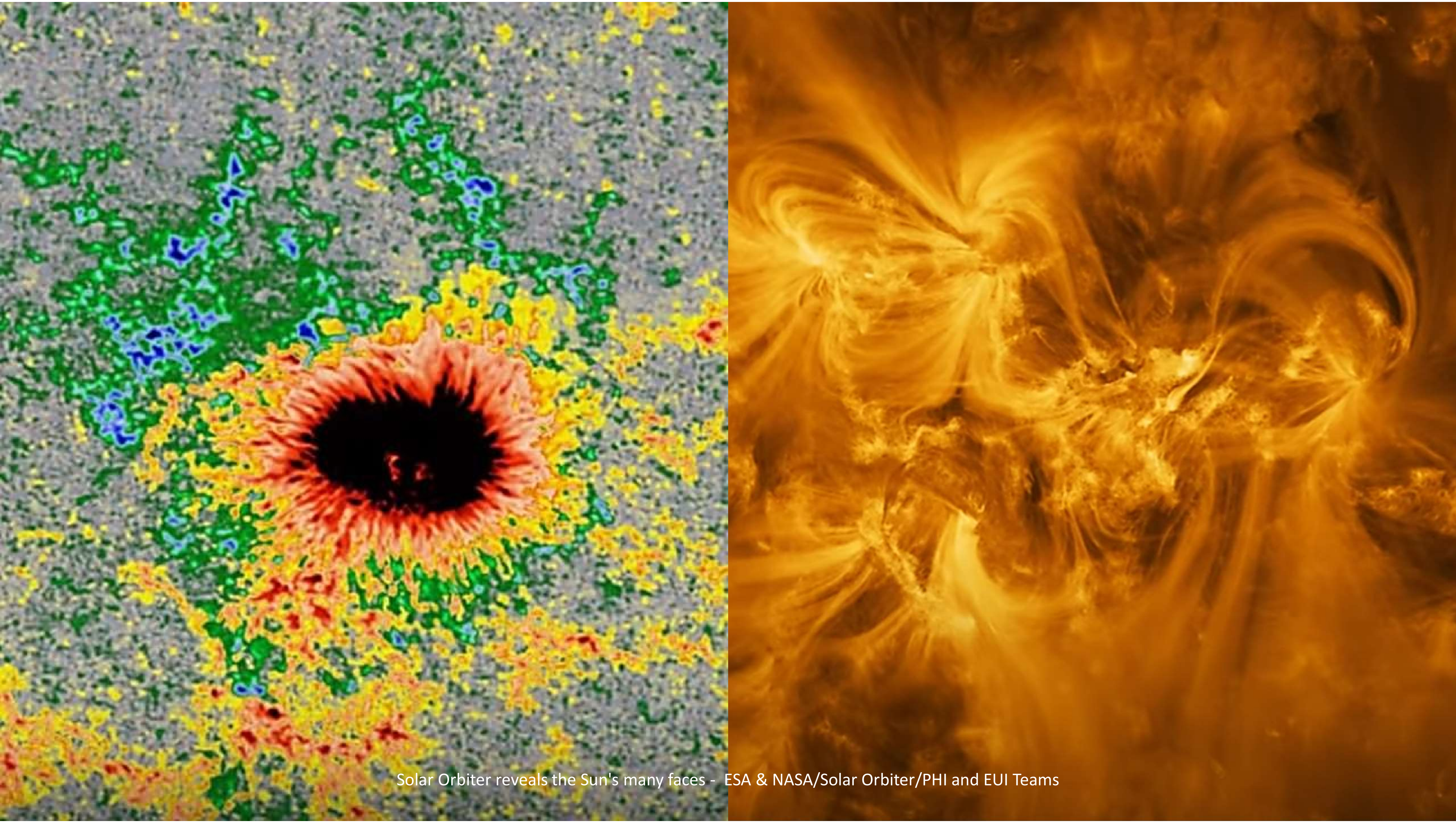
Motivations


31. 08. 2012 19:44:11

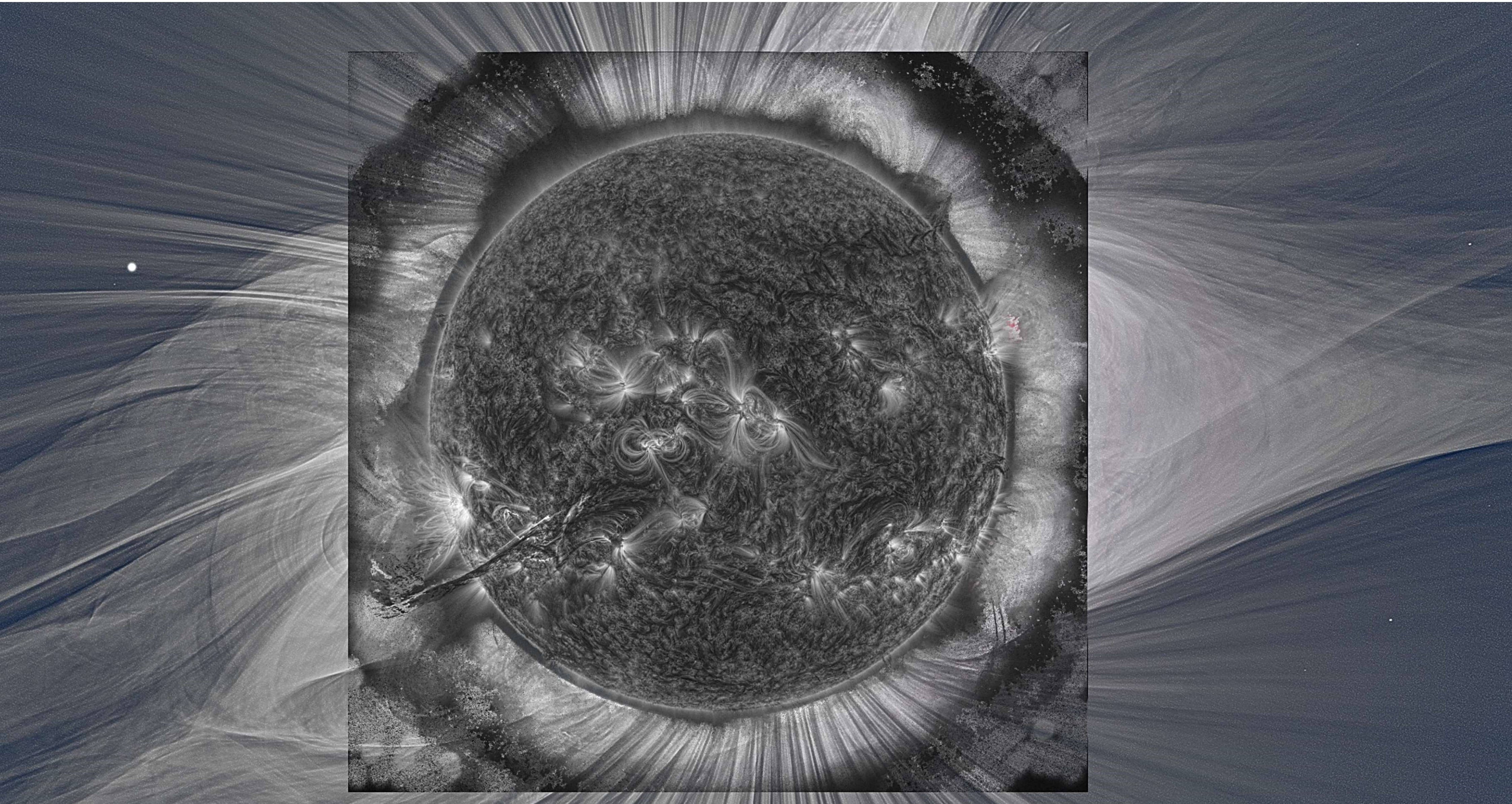
Magnetic Activity Areas, Sunspots, Flares and Coronal Mass Ejections
SDO/NASA/GSFC/M. Druckmüller (PM-NAFE)


X3.1 Flare, October 24, 2014
SDO AIA 304 A, 171 A, 211 A, PM-NAFE processing & HMI
Sunspot 2192
© 2015 Miloslav Druckmüller

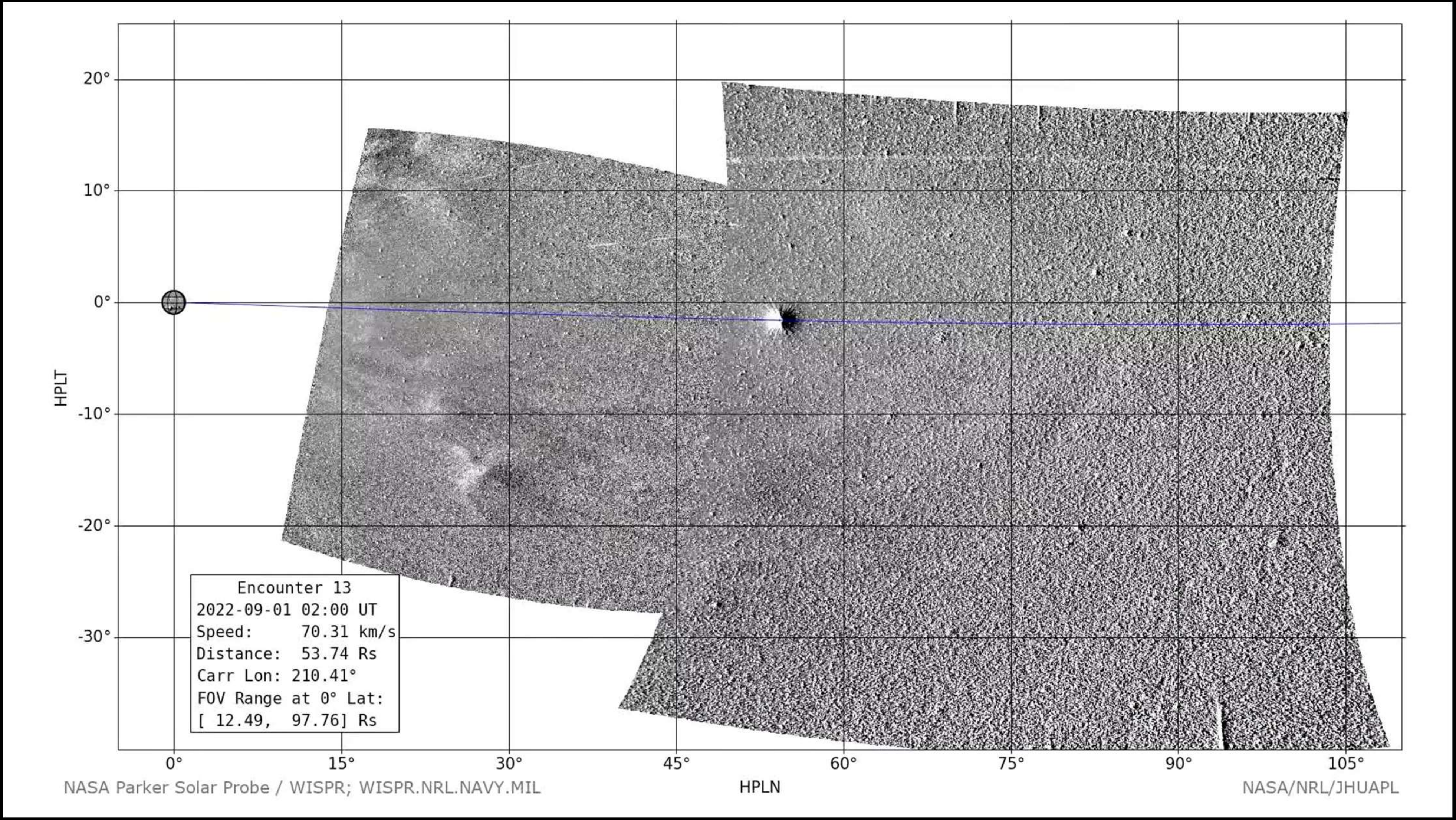




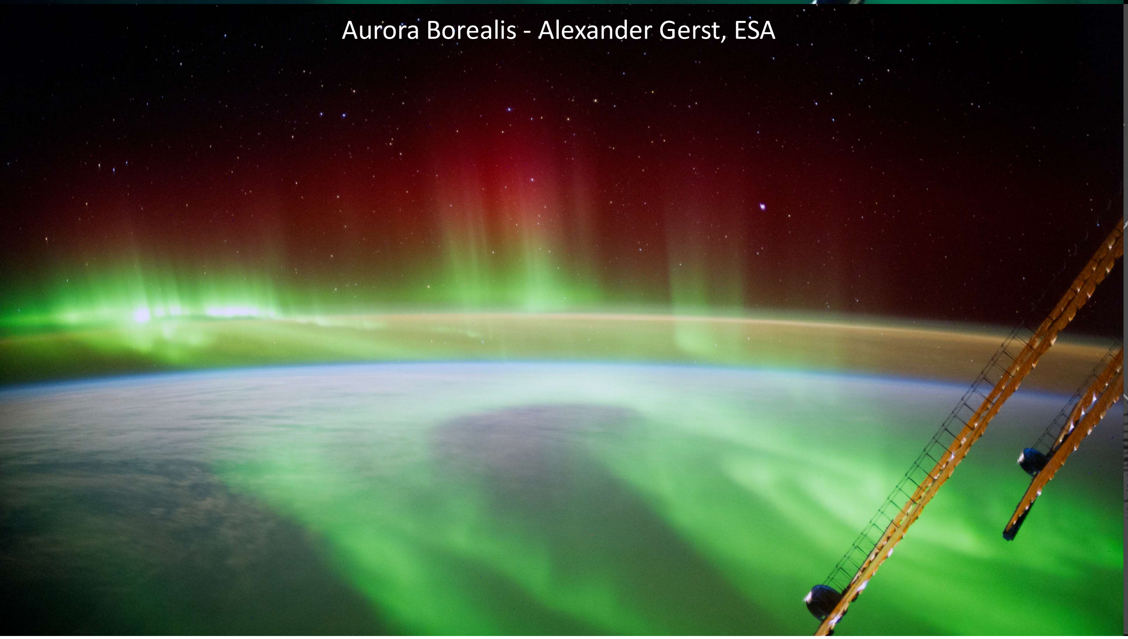
Solar Orbiter reveals the Sun's many faces - ESA & NASA/Solar Orbiter/PHI and EUI Teams



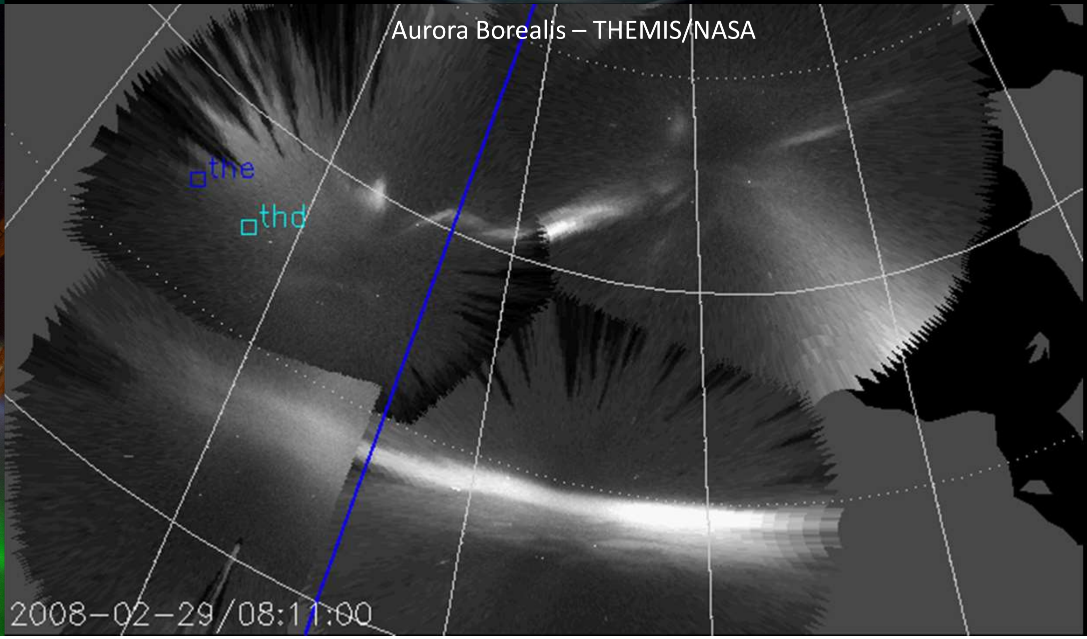
The Magnetic Sun, Corona and Solar Wind
SDO/NASA/GSFC/M. Druckmüller (PM-NAFE)/U. v. Kusserow (Editing)



Conversion of measured signals into audio signals during a coronal mass ejection
NASA/Johns Hopkins APL/Naval Research Laboratory/Brendan Gallagher/Guillermo Stenborg/Emmanuel Masongsong/Lizet Casillas/Robert Alexander/David Malaspina



Aurora Borealis - Alexander Gerst, ESA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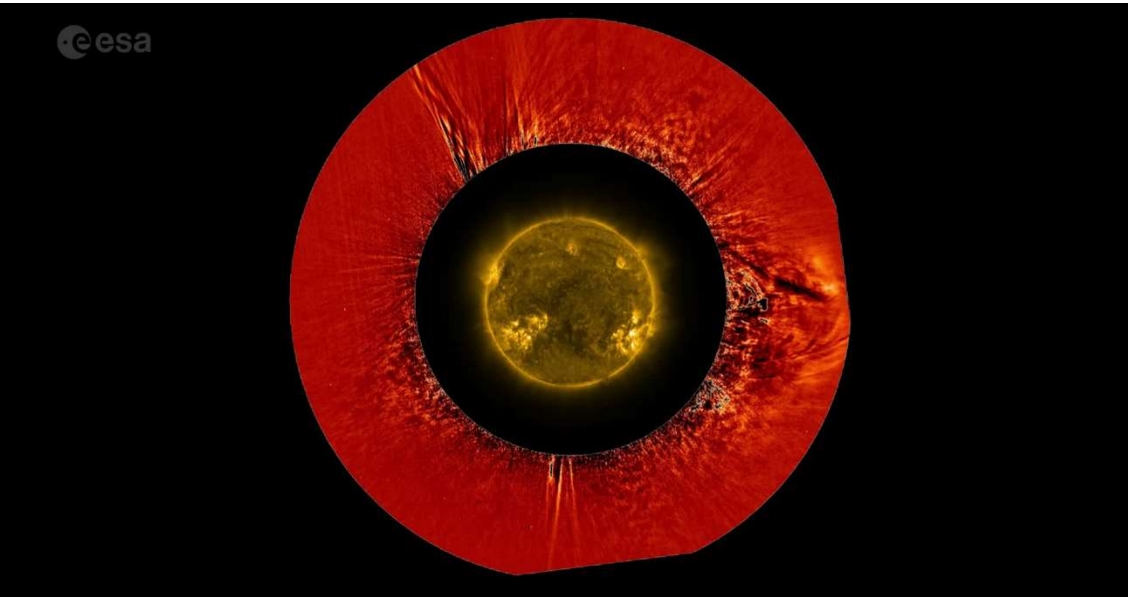
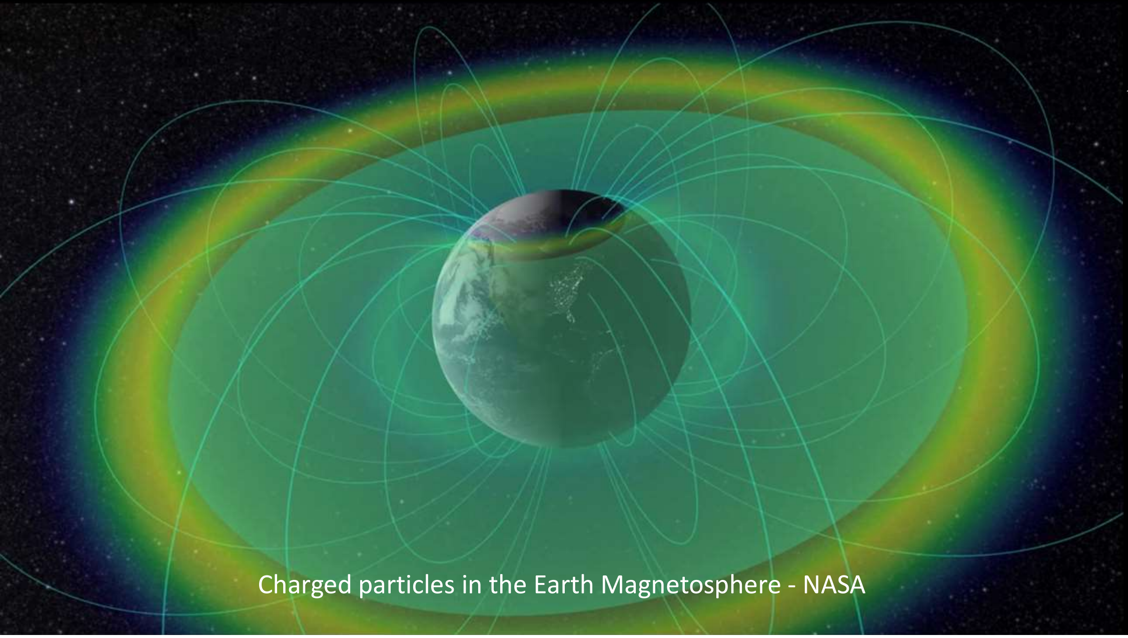
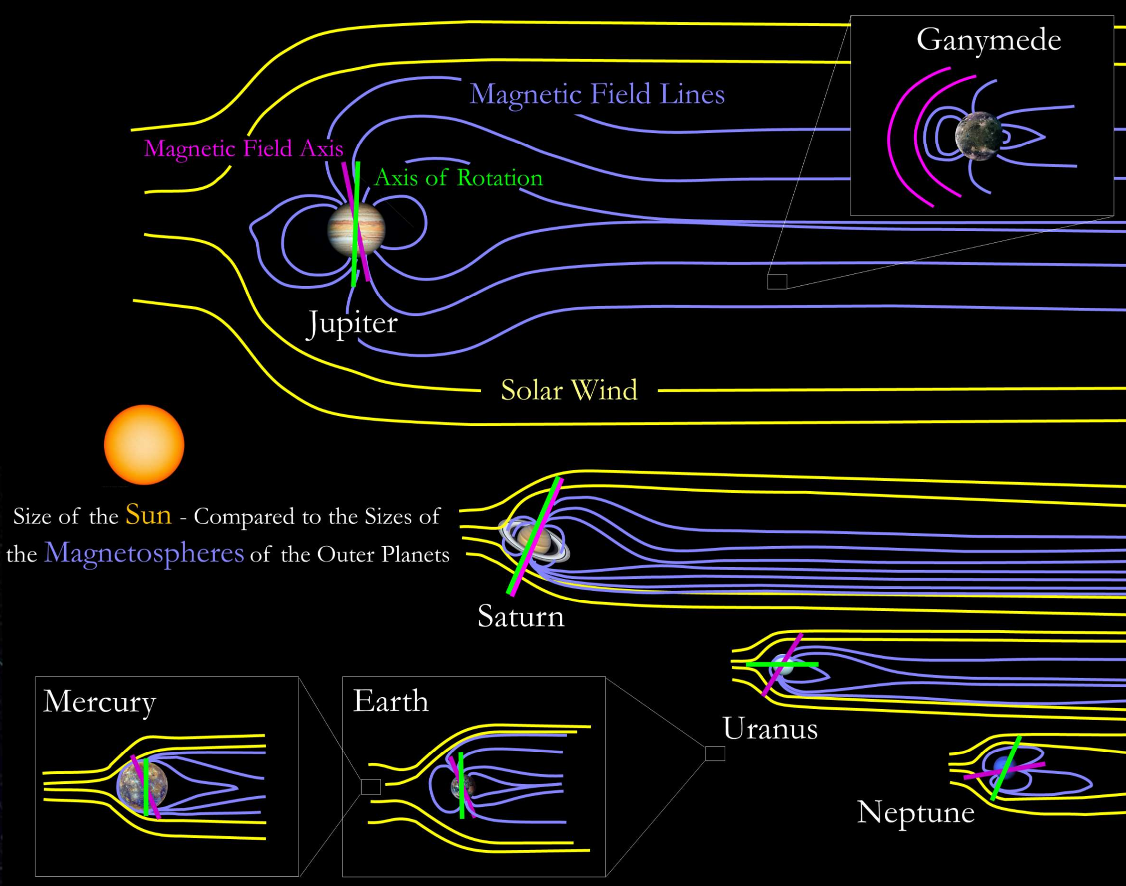
Aurora Borealis – THEMIS/NASA



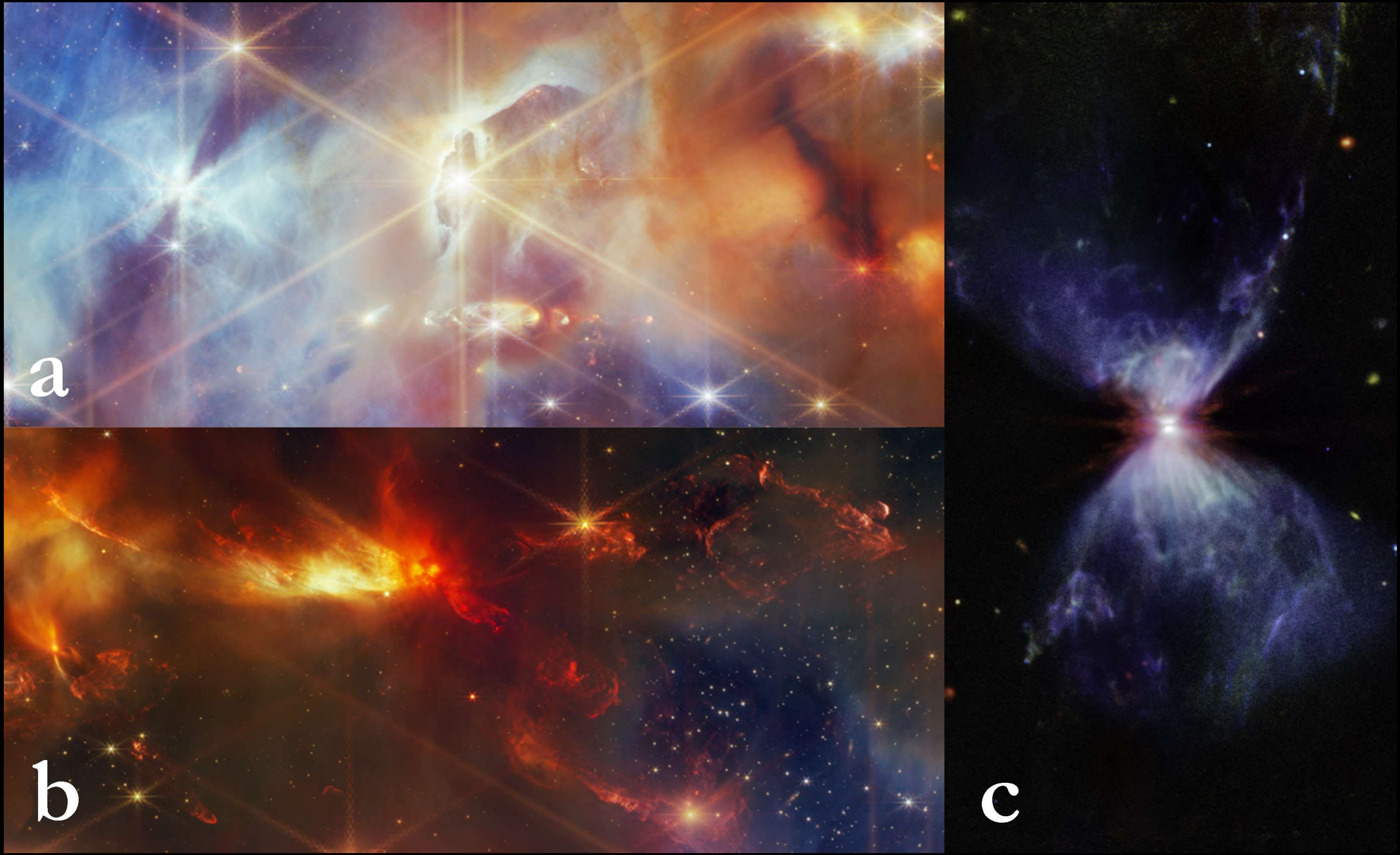
Solar Corona Turbulence - ESA & NASA/Solar Orbiter/Metis & EUI Teams and D. Telloni/INAF



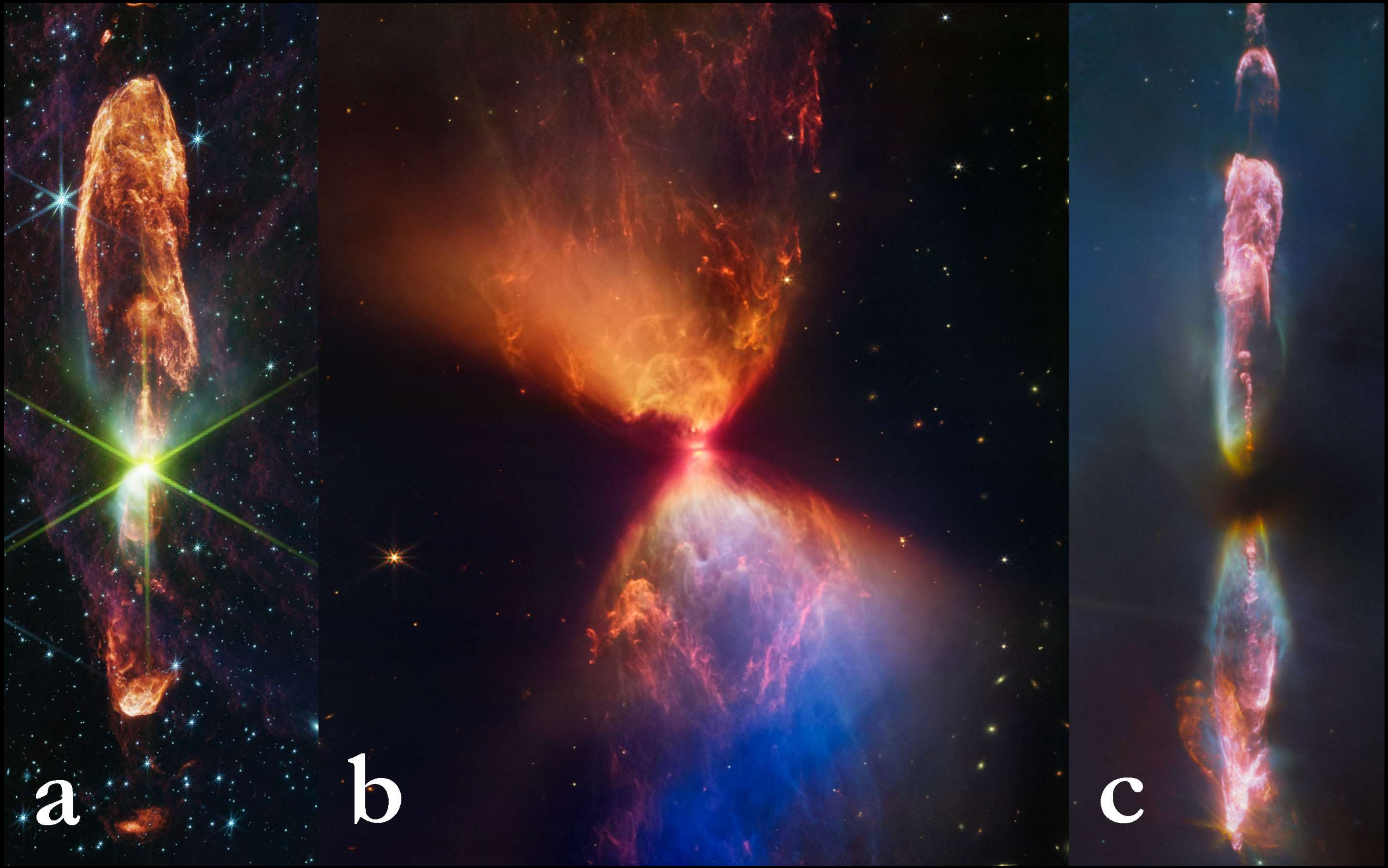
Charged particles in the Earth Magnetosphere - NASA


Ganymede
Magnetic Field Lines
Magnetic Field Axis
Axis of Rotation
Jupiter
Solar Wind
Size of the Sun - Compared to the Sizes of the Magnetospheres of the Outer Planets
Saturn
Mercury
Earth
Uranus
Neptune

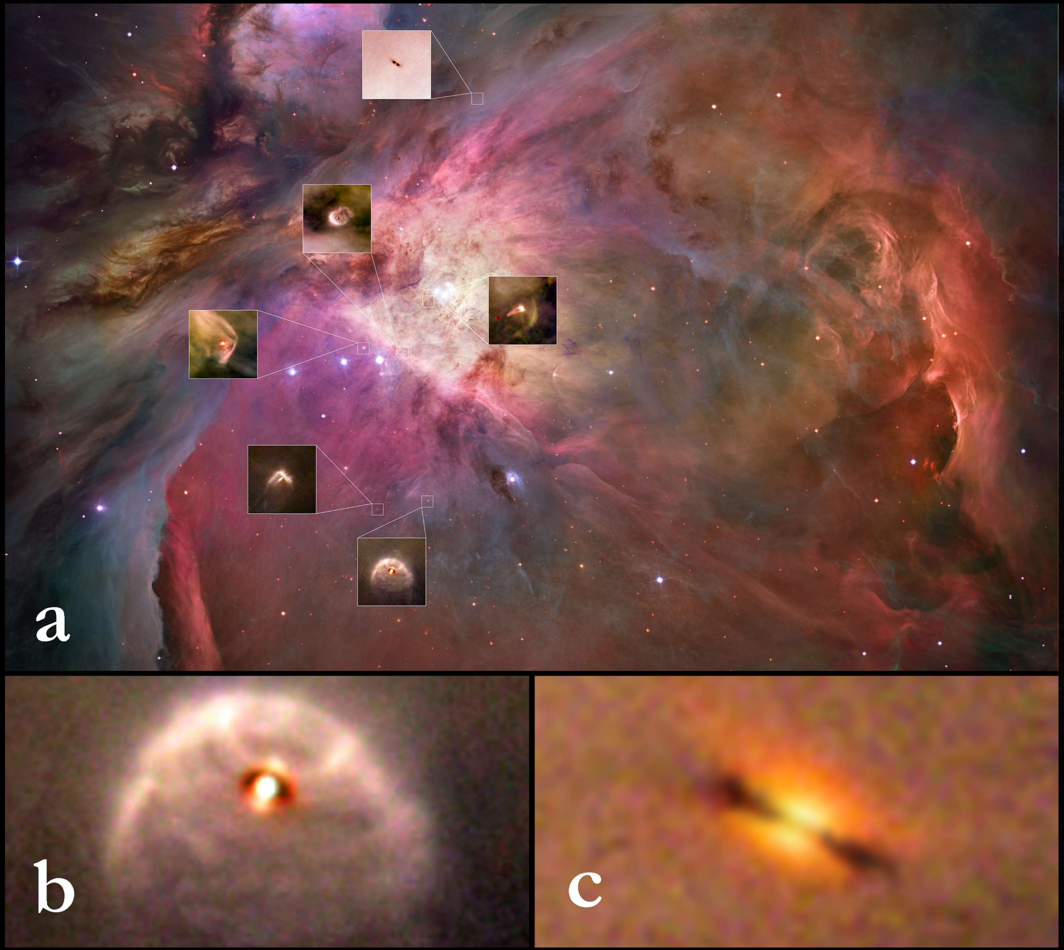
Magnetospheres of Planets and the Moon Ganymed in the Solar System - U. v. Kusserow/NASA



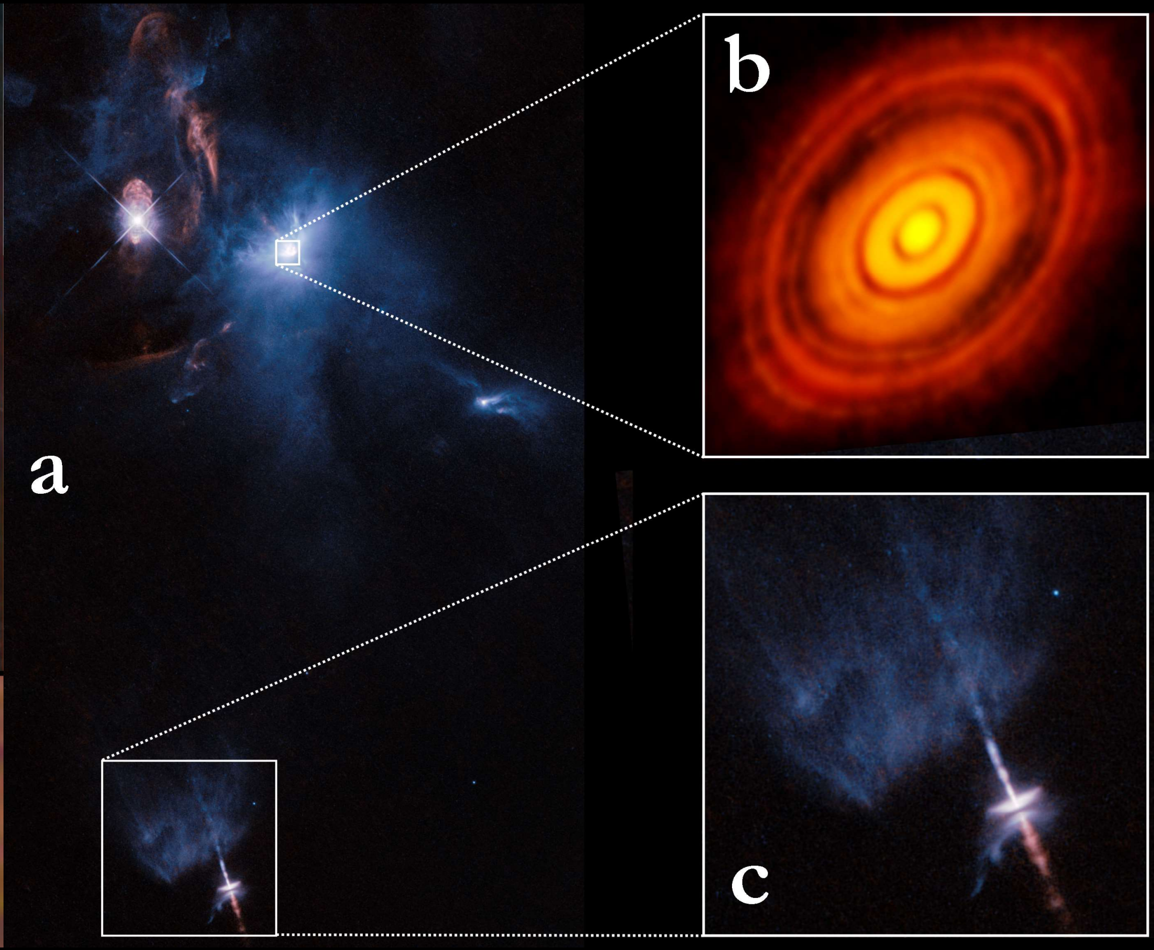
Infrared images of protostellar disk-jet structures taken with the James Webb Space Telescope. **a** Molecular clouds, **b** jets in the constellation Cygnus, **c** L 1527
NASA/ESA/CSA/STScI/K. Pontoppidan (NASA-JPL) /J. Green (STScI) (2), NASA/ESA/CSA/STScI



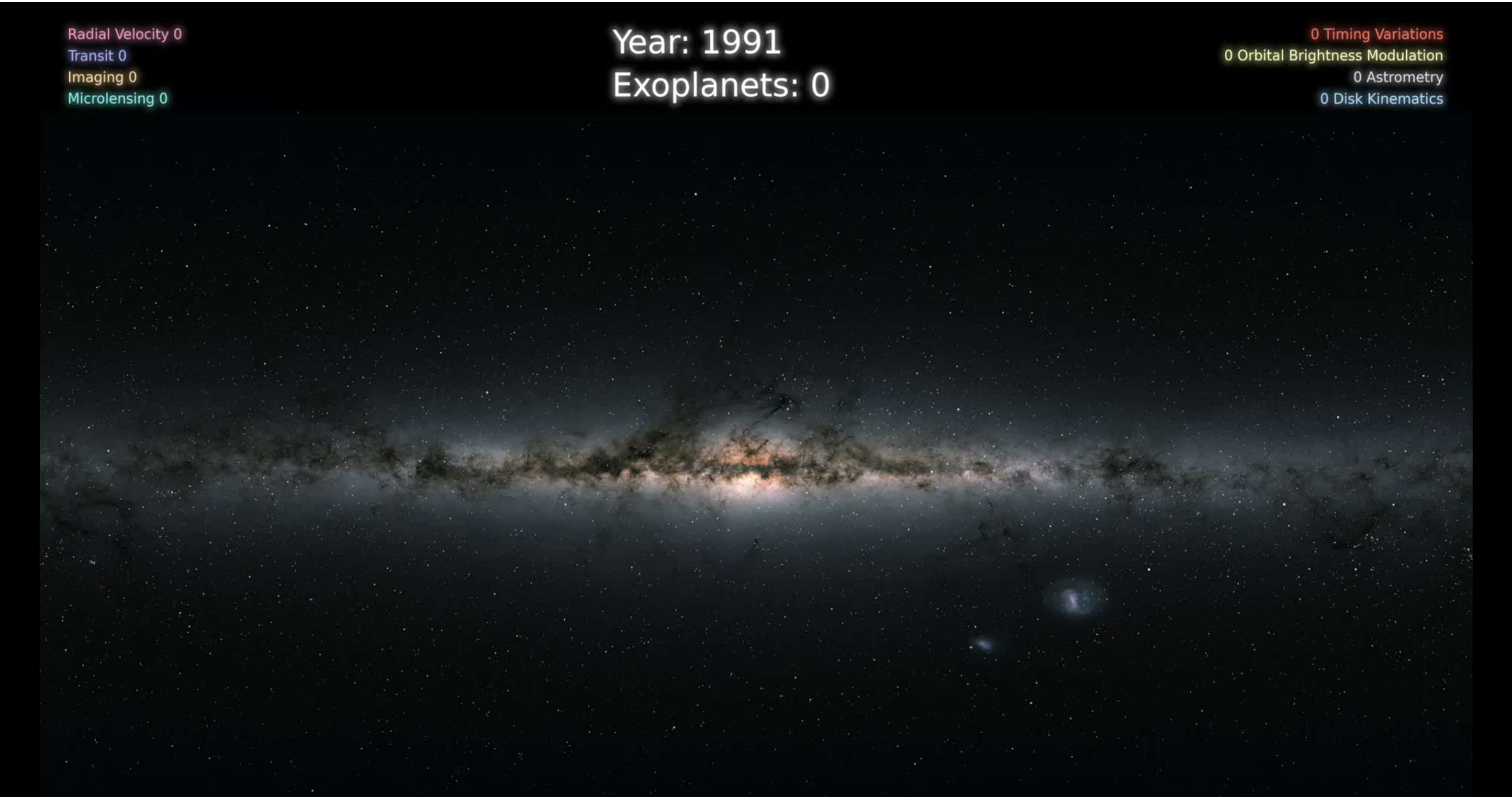
Infrared images of the James Webb Space Telescope of stellar winds and Herbig-Haro objects of protostellar systems. **a** HH 46/47, b L 1527, c HH 2011
NASA/ESA/CSA/STScI/J. DePasquale/A. M. Koekemoer, J. DePasquale/A. Pagan/A. M. Koekemoer, T. Ray (DIAS Dublin)



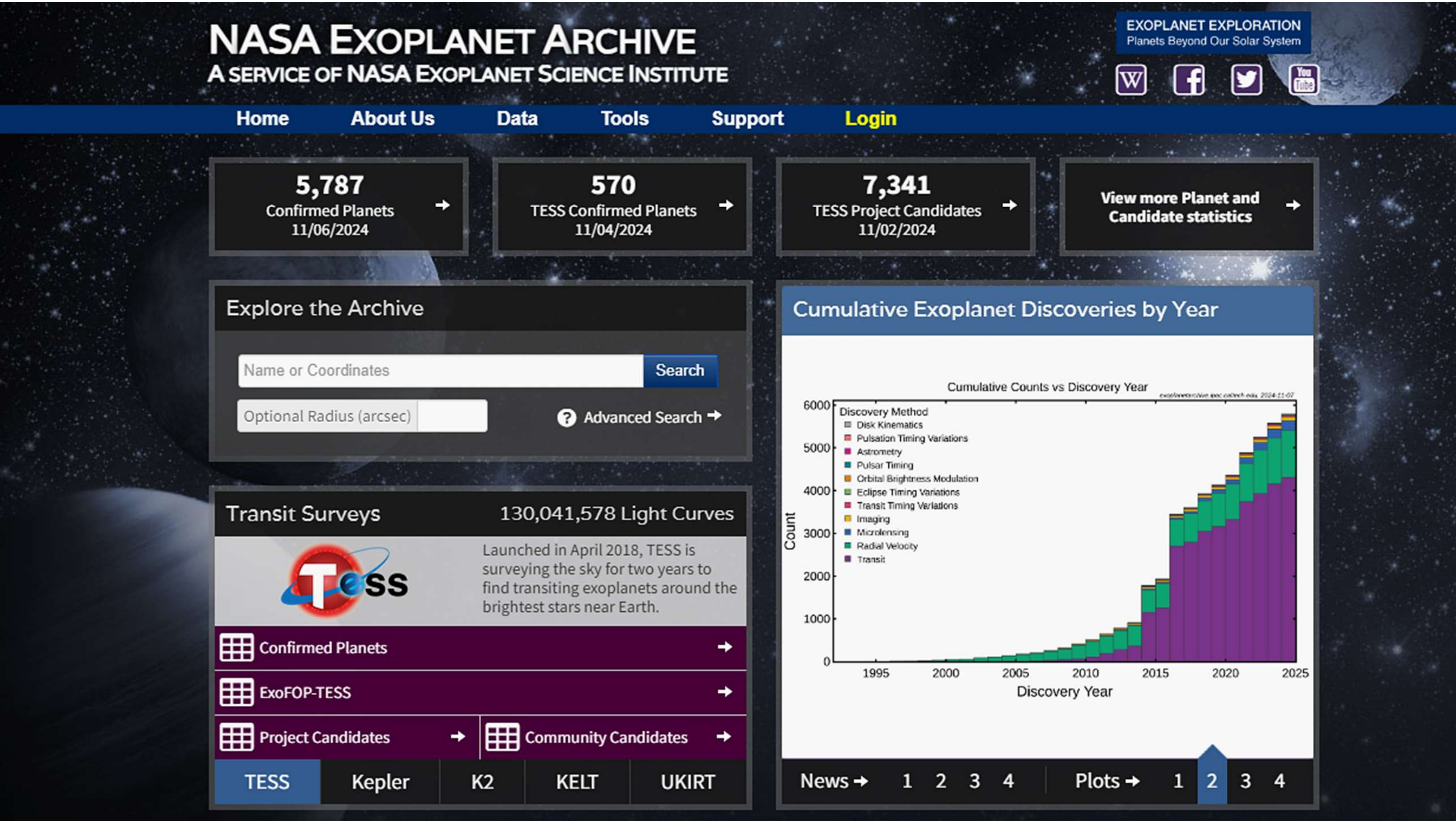
Proplyds in **a** the Orion Nebula, **b** Proplyd 473-245, **c** Proplyd 181-825
NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA), the Hubble Space Telescope Orion Treasury Project Team and L. Ricci (ESO)



Gas clouds and radiation bursts of jet-like bundled winds and accretion disks in the vicinity of the young stars XZ Tauri, HL Tauri and V1213 Tauri in the constellation Taurus
ESA/Hubble und NASA, ALMA (ESO/NAOJ/NRAO), (Editing: U. v. Kusserow)


Radial Velocity 0
Transit 0
Imaging 0
Microlensing 0
Year: 1991
Exoplanets: 0
0 Timing Variations
0 Orbital Brightness Modulation
0 Astrometry
0 Disk Kinematics

5,000 Exoplanets: Listen to the Sounds of Discovery (until March 21, 2022) - NASA/JPL-Caltech/M. Russo, A. Santaguida (SYSTEM Sounds)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5,787 Confirmed Planets 11/06/2024

570 TESS Confirmed Planets 11/04/2024

7,341 TESS Project Candidates 11/02/2024

View more Planet and Candidate statistics
Explore the Archive
Name or Coordinates
Search
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Advanced Search
Transit Surveys

130,041,578 Light Curves

Launched in April 2018, TESS is surveying the sky for two years to find transiting exoplanets around the brightest stars near Earth.

Confirmed Planets
ExoFOP-TESS
Project Candidates
Community Candidates
TESS
Kepler
K2
KELT
UKIRT
Cumulative Exoplanet Discoveries by Year
Cumulative Counts vs Discovery Year
exoplanetarchive.ipac.caltech.edu, 2024-11-07
Discovery Method
Disk Kinematics
Pulsation Timing Variations
Astrometry
Pulsar Timing
Orbital Brightness Modulation
Eclipse Timing Variations
Transit Timing Variations
Imaging
Microlensing
Radial Velocity
Transit
Count
0
1000
2000
3000
4000
5000
6000
1995
2000
2005
2010
2015
2020
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Discovery Year
News
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2
3
4
Plots
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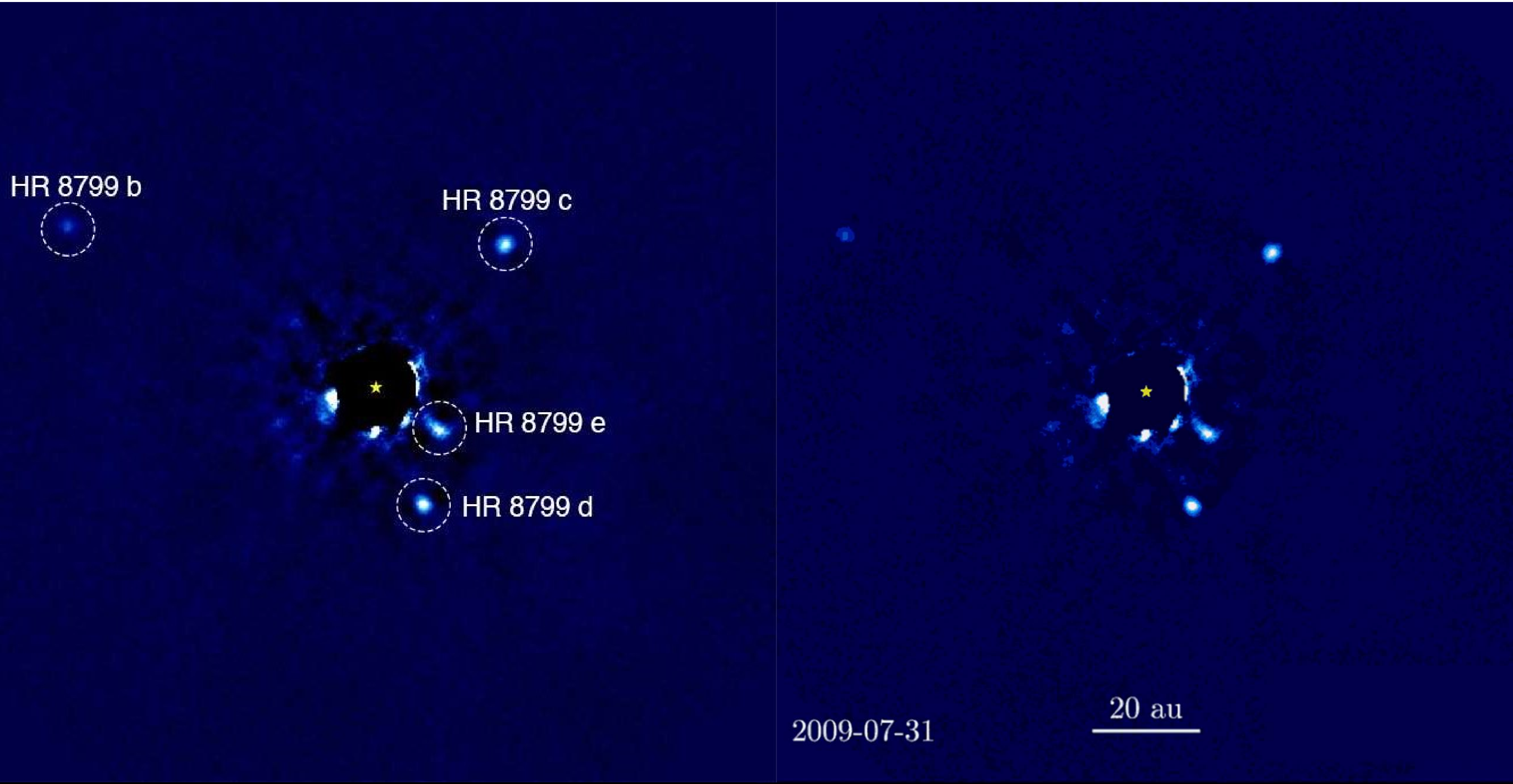
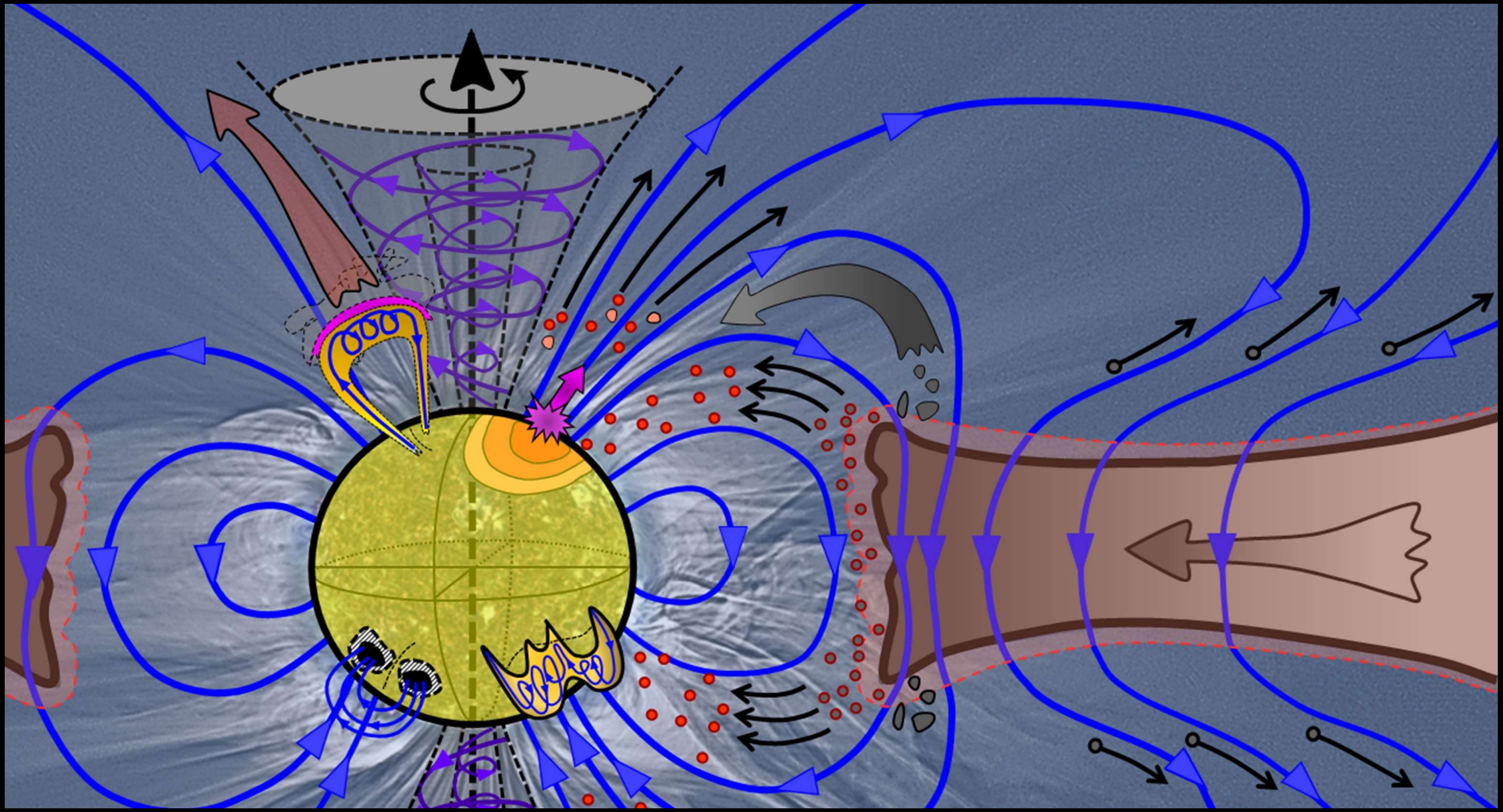
4

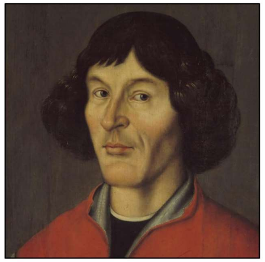

HR 8799 b
HR 8799 c
HR 8799 e
HR 8799 d
2009-07-31
20 au

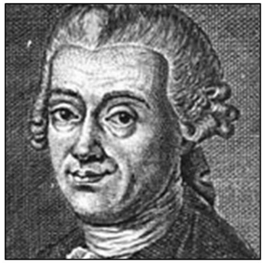
Orbit of the four exoplanets around the star HR 8799- Jason Wang et al.

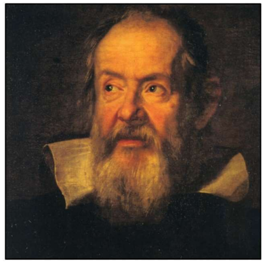


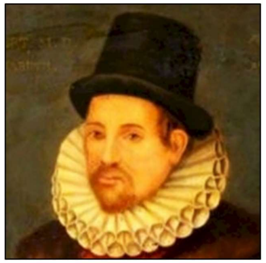
$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{B}) - \vec{\nabla} \times (\eta_{\mathrm{OD}} \cdot \vec{\nabla} \times \vec{B}) + \vec{\nabla} \times \{\eta_{\mathrm{AD}} \cdot (\vec{\nabla} \times \vec{B}) \times \vec{B}\} - \vec{\nabla} \times [\vec{\nabla} \times \{\eta_{\mathrm{HD}} \cdot (\vec{\nabla} \times \vec{B}) \times \vec{B}\}]$$

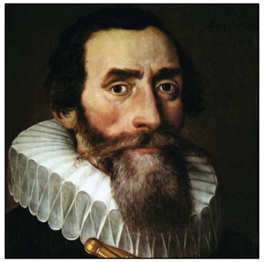
Historical Reference

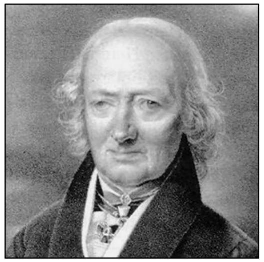

Nikolaus Kopernikus
(1473-1543))

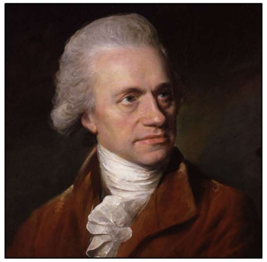

Johann Daniel Titius
(1729-1796)

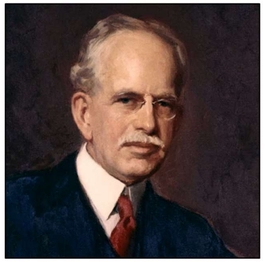

Galileo Galilei
(1564-1641)

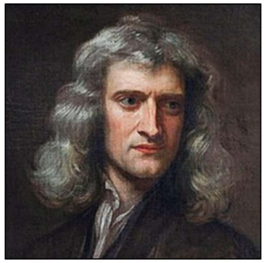

William Gilbert
(1544-1603)

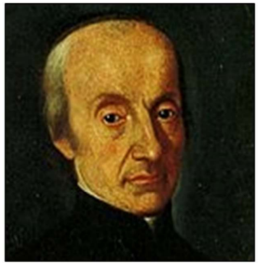

Johannes Kepler
(1571-1630)

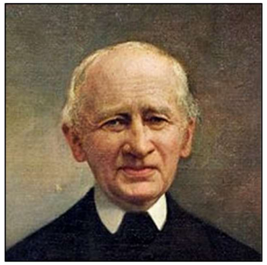

Johann Elert Bode
(1747-1826)

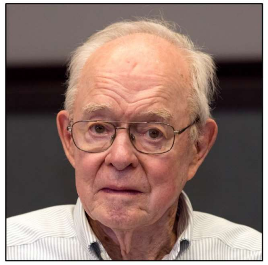

Wilhelm Herschel
(1738-1822)

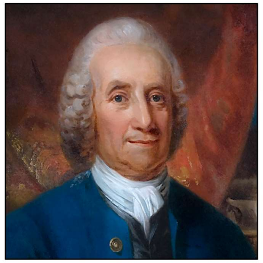

George Ellery Hale
(1868-1938)


Isaac Newton
(1643-1727)


Giuseppe Piazzi
(1746-1826)


Johann Gottfried Galle
(1746-1826)

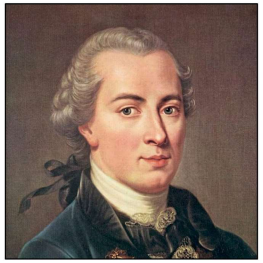

Eugen Newman Parker
(1927-2022)

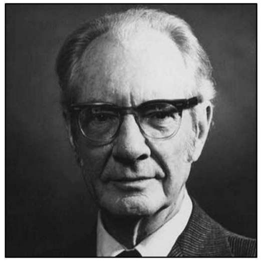

Emanuel Swedenborg
(1688-1772)

James H. Jeans
(1912-2007)

Gerard Peter Kuiper
(1905-1973)

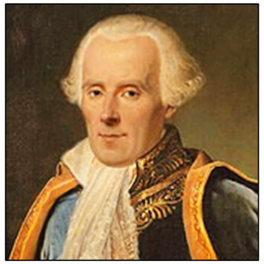
Viktor S. Safronov
(1917-1999)

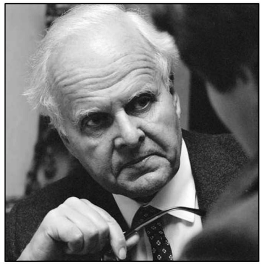

Immanuel Kant
(1724-1804)

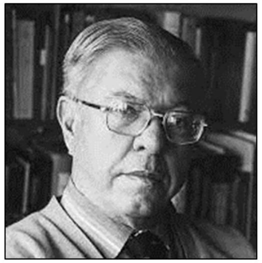

Fred Lawrence Whipple
(1906-2004)

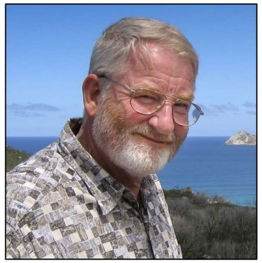
Hannes O. G. Alfvén
(1908-1995)

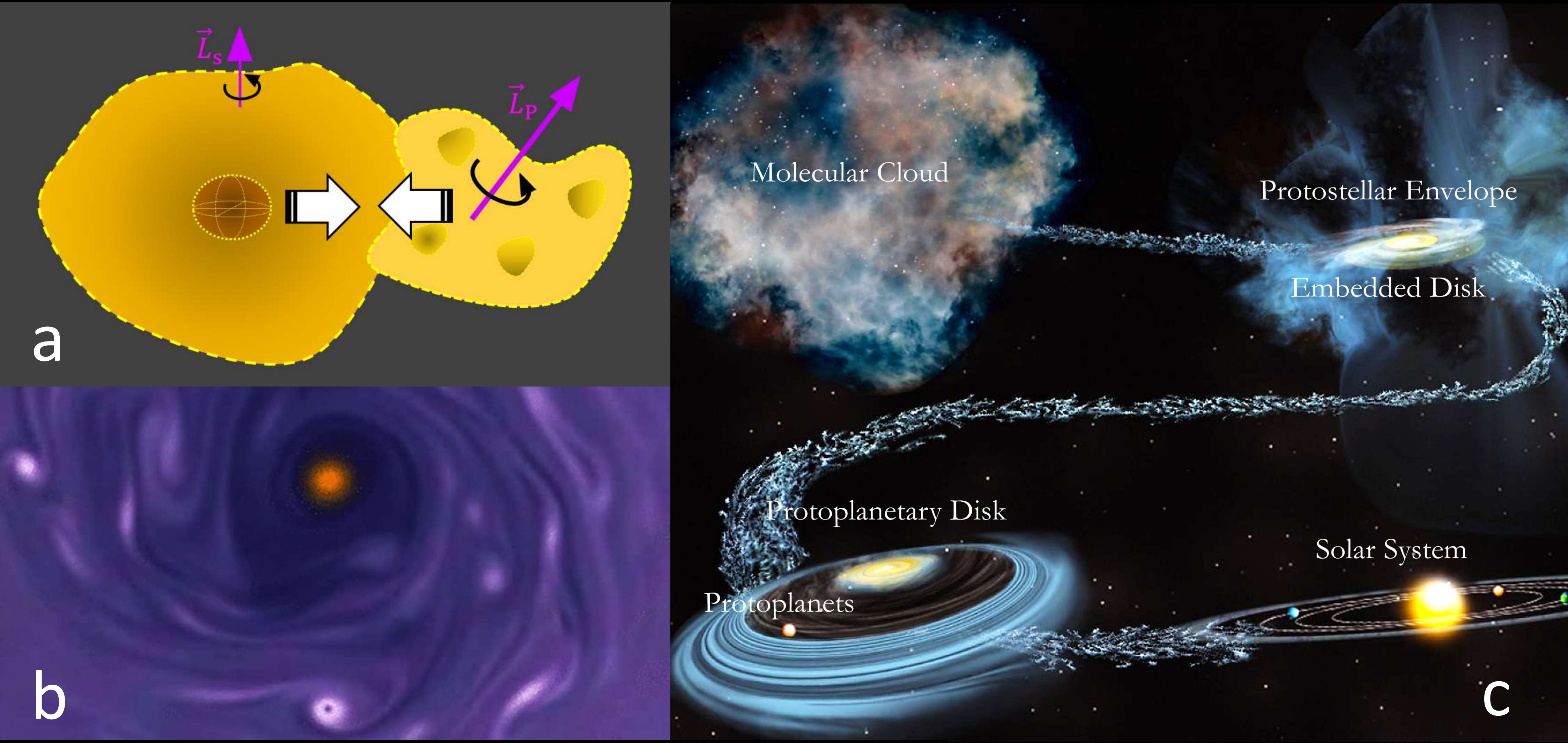
Richard Larson


Pierre-Simon Laplace
(1749-1827)


Carl-Fr. v. Weizsäcker
(1912-2007)

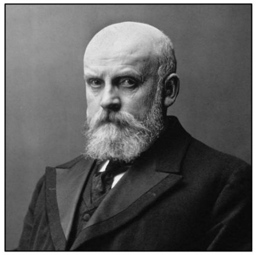

Fred Hoyle
(1915-2001)


Andrew J. R. Prentice

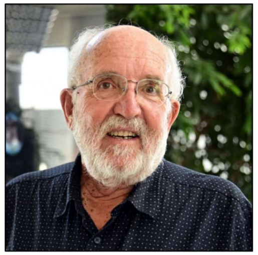

$\vec{L}_\mathrm{S}$
$\vec{L}_\mathrm{P}$
a
b
Molecular Cloud
Protostellar Envelope
Embedded Disk
Protoplanetary Disk
Protoplanets
Solar System
c

Simple models for the formation of the solar system through **a** collision processes, **b** turbulence and **c** within the framework of the modern nebular hypothesis

U. v. Kusserow, J. S. Wettlaufer, B. Saxton/NSF/AUI/NRAO

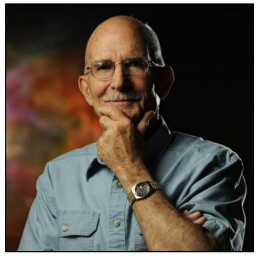

John Russell Hind
(1823-1895)

Guillermo Haro
(1913-1988)


Michel Mayor

Gibor Basri

Sherburne W. Burnham
(1838-1921)


Charles Robert O´Dell

Didier Queloz

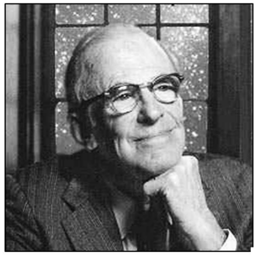
Jean-François Donati

George H. Herbig
(1920-2013)

Mark J. McCaughrean

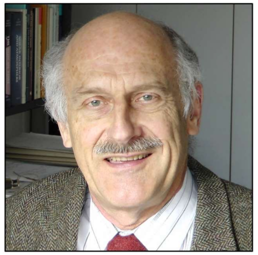
Gaël Chauvin

Chin-Fei Lee


Lyman Spitzer
(1914-1997)

Telemachos Mouschovias

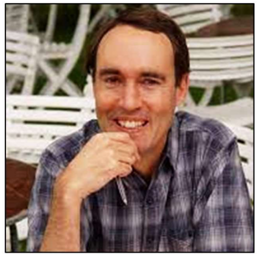
John Hawley
(1958-2021)


Hendrik Spruit

Leon Mestel
(1927-2017)

Nikolay Shakura
Rashid Sunyaev

Roger Blandford


Matthew R. Bate

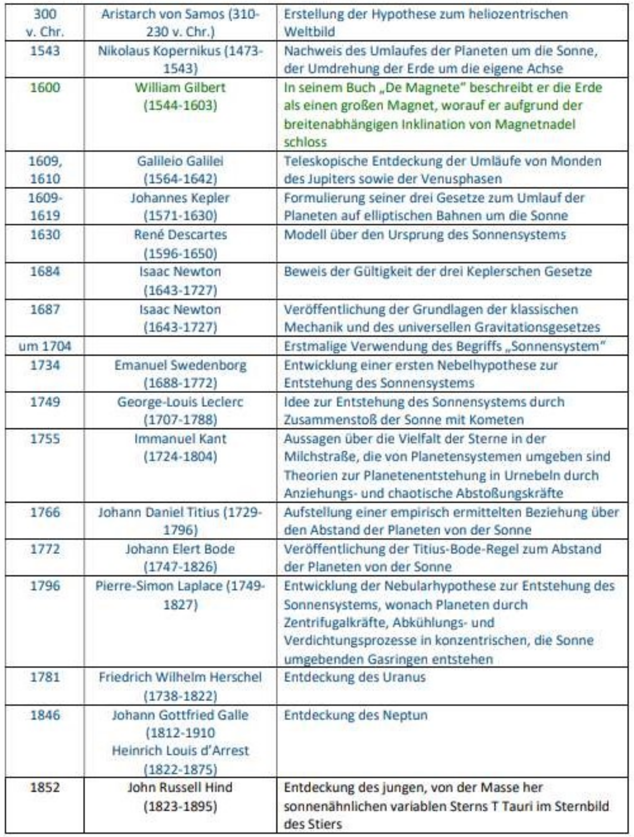
Frank H.-S. Shu
(1943-2023)

Steven Andrew Balbus

David G. Payne

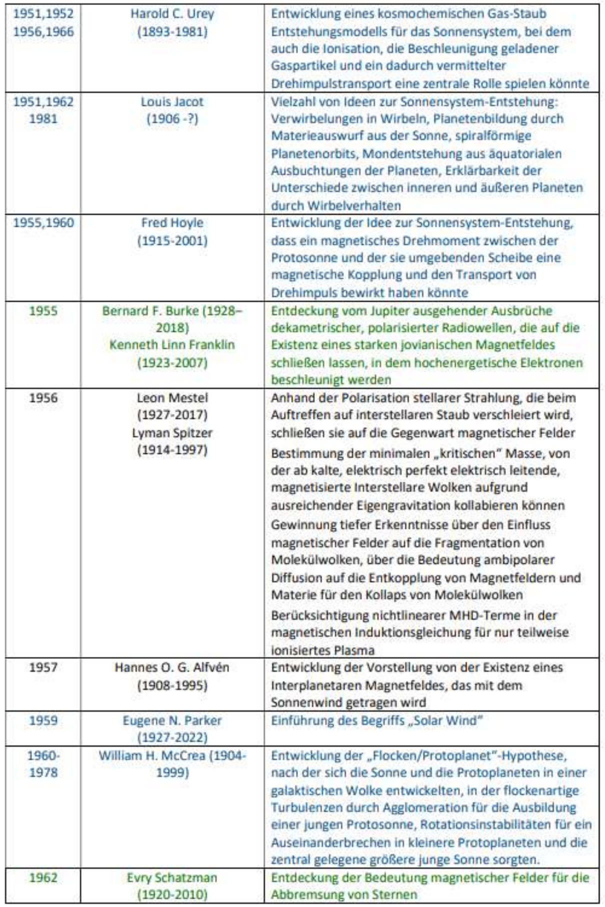
Axel Brandenburg

Historical Discoveries related to the Formation of Extrasolar Star Systems and our Solar System also under Magnetic Influence



300 v. Chr.	Aristarch von Samos (310-230 v. Chr.)	Erstellung der Hypothese zum heliozentrischen Weltbild
1543	Nikolaus Kopernikus (1473-1543)	Nachweis des Umlaufes der Planeten um die Sonne, der Umdrehung der Erde um die eigene Achse
1600	William Gilbert (1544-1603)	In seinem Buch „De Magnete" beschreibt er die Erde als einen großen Magnet, worauf er aufgrund der breitenabhängigen Inklination von Magnetnadel schloss
1609, 1610	Galileio Galilei (1564-1642)	Teleskopische Entdeckung der Umläufe von Monden des Jupiters sowie der Venusphasen
1609-1619	Johannes Kepler (1571-1630)	Formulierung seiner drei Gesetze zum Umlauf der Planeten auf elliptischen Bahnen um die Sonne
1630	René Descartes (1596-1650)	Modell über den Ursprung des Sonnensystems
1684	Isaac Newton (1643-1727)	Beweis der Gültigkeit der drei Keplerschen Gesetze
1687	Isaac Newton (1643-1727)	Veröffentlichung der Grundlagen der klassischen Mechanik und des universellen Gravitationsgesetzes
um 1704		Erstmalige Verwendung des Begriffs „Sonnensystem"
1734	Emanuel Swedenborg (1688-1772)	Entwicklung einer ersten Nebelhypothese zur Entstehung des Sonnensystems
1749	George-Louis Leclerc (1707-1788)	Idee zur Entstehung des Sonnensystems durch Zusammenstoß der Sonne mit Kometen
1755	Immanuel Kant (1724-1804)	Aussagen über die Vielfalt der Sterne in der Milchstraße, die von Planetensystemen umgeben sind Theorien zur Planetenentstehung in Urnebeln durch Anziehungs- und chaotische Abstoßungskräfte
1766	Johann Daniel Titius (1729-1796)	Aufstellung einer empirisch ermittelten Beziehung über den Abstand der Planeten von der Sonne
1772	Johann Elert Bode (1747-1826)	Veröffentlichung der Titius-Bode-Regel zum Abstand der Planeten von der Sonne
1796	Pierre-Simon Laplace (1749-1827)	Entwicklung der Nebularhypothese zur Entstehung des Sonnensystems, wonach Planeten durch Zentrifugalkräfte, Abkühlungs- und Verdichtungsprozesse in konzentrischen, die Sonne umgebenden Gasringen entstehen
1781	Friedrich Wilhelm Herschel (1738-1822)	Entdeckung des Uranus
1846	Johann Gottfried Galle (1812-1910 Heinrich Louis d'Arrest (1822-1875)	Entdeckung des Neptun
1852	John Russell Hind (1823-1895)	Entdeckung des jungen, von der Masse her sonnenähnlichen variablen Sterns T Tauri im Sternbild des Stiers

• • •



1951,1952 1956,1966	Harold C. Urey (1893-1981)	Entwicklung eines kosmochemischen Gas-Staub Entstehungsmodells für das Sonnensystem, bei dem auch die Ionisation, die Beschleunigung geladener Gaspartikel und ein dadurch vermittelter Drehimpulstransport eine zentrale Rolle spielen könnte
1951,1962 1981	Louis Jacot (1906 -?)	Vielzahl von Ideen zur Sonnensystem-Entstehung: Verwirbelungen in Wirbeln, Planetenbildung durch Materieauswurf aus der Sonne, spiralförmige Planetenorbits, Mondentstehung aus äquatorialen Ausbuchtungen der Planeten, Erklärbarkeit der Unterschiede zwischen inneren und äußeren Planeten durch Wirbelverhalten
1955,1960	Fred Hoyle (1915-2001)	Entwicklung der Idee zur Sonnensystem-Entstehung, dass ein magnetisches Drehmoment zwischen der Protosonne und der sie umgebenden Scheibe eine magnetische Kopplung und den Transport von Drehimpuls bewirkt haben könnte
1955	Bernard F. Burke (1928–2018) Kenneth Linn Franklin (1923-2007)	Entdeckung vom Jupiter ausgehender Ausbrüche dekametrischer, polarisierter Radiowellen, die auf die Existenz eines starken jovianischen Magnetfeldes schließen lassen, in dem hochenergetische Elektronen beschleunigt werden
1956	Leon Mestel (1927-2017) Lyman Spitzer (1914-1997)	Anhand der Polarisation stellarer Strahlung, die beim Auftreffen auf interstellaren Staub verschleiert wird, schließen sie auf die Gegenwart magnetischer Felder Bestimmung der minimalen „kritischen" Masse, von der ab kalte, elektrisch perfekt elektrisch leitende, magnetisierte Interstellare Wolken aufgrund ausreichender Eigengravitation kollabieren können Gewinnung tiefer Erkenntnisse über den Einfluss magnetischer Felder auf die Fragmentation von Molekülwolken, über die Bedeutung ambipolarer Diffusion auf die Entkopplung von Magnetfeldern und Materie für den Kollaps von Molekülwolken Berücksichtigung nichtlinearer MHD-Terme in der magnetischen Induktionsgleichung für nur teilweise ionisiertes Plasma
1957	Hannes O. G. Alfvén (1908-1995)	Entwicklung der Vorstellung von der Existenz eines Interplanetaren Magnetfeldes, das mit dem Sonnenwind getragen wird
1959	Eugene N. Parker (1927-2022)	Einführung des Begriffs „Solar Wind"
1960-1978	William H. McCrea (1904-1999)	Entwicklung der „Flocken/Protoplanet"-Hypothese, nach der sich die Sonne und die Protoplaneten in einer galaktischen Wolke entwickelten, in der flockenartige Turbulenzen durch Agglomeration für die Ausbildung einer jungen Protosonne, Rotationsinstabilitäten für ein Auseinanderbrechen in kleinere Protoplaneten und die zentral gelegene größere junge Sonne sorgten.
1962	Evry Schatzman (1920-2010)	Entdeckung der Bedeutung magnetischer Felder für die Abbremsung von Sternen

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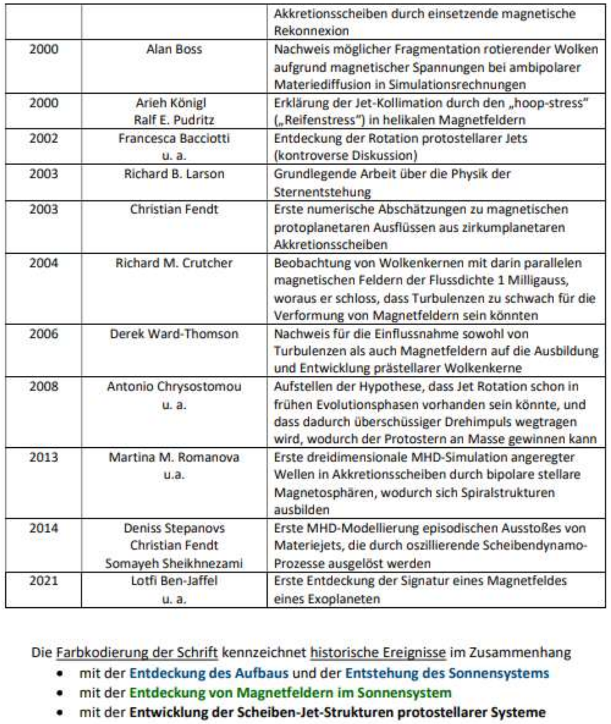
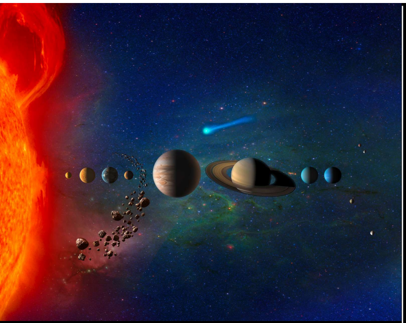


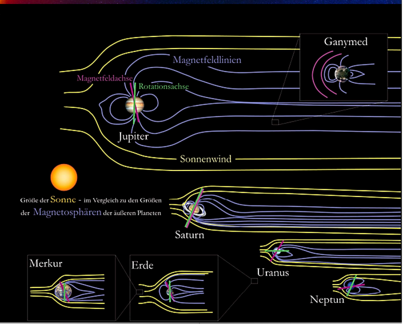
		Akkretionsscheiben durch einsetzende magnetische Rekonnexion
2000	Alan Boss	Nachweis möglicher Fragmentation rotierender Wolken aufgrund magnetischer Spannungen bei ambipolarer Materiediffusion in Simulationsrechnungen
2000	Arieh Königl Ralf E. Pudritz	Erklärung der Jet-Kollimation durch den „hoop-stress" („Reifenstress") in helikalen Magnetfeldern
2002	Francesca Bacciotti u. a.	Entdeckung der Rotation protostellarer Jets (kontroverse Diskussion)
2003	Richard B. Larson	Grundlegende Arbeit über die Physik der Sternentstehung
2003	Christian Fendt	Erste numerische Abschätzungen zu magnetischen protoplanetaren Ausflüssen aus zirkumplanetaren Akkretionsscheiben
2004	Richard M. Crutcher	Beobachtung von Wolkenkernen mit darin parallelen magnetischen Feldern der Flussdichte 1 Milligauss, woraus er schloss, dass Turbulenzen zu schwach für die Verformung von Magnetfeldern sein könnten
2006	Derek Ward-Thomson	Nachweis für die Einflussnahme sowohl von Turbulenzen als auch Magnetfeldern auf die Ausbildung und Entwicklung prästellarer Wolkenkerne
2008	Antonio Chrysostomou u. a.	Aufstellen der Hypothese, dass Jet Rotation schon in frühen Evolutionsphasen vorhanden sein könnte, und dass dadurch überschüssiger Drehimpuls wegtragen wird, wodurch der Protostern an Masse gewinnen kann
2013	Martina M. Romanova u.a.	Erste dreidimensionale MHD-Simulation angeregter Wellen in Akkretionsscheiben durch bipolare stellare Magnetosphären, wodurch sich Spiralstrukturen ausbilden
2014	Deniss Stepanovs Christian Fendt Somayeh Sheikhnezami	Erste MHD-Modellierung episodischen Ausstoßes von Materiejets, die durch oszillierende Scheibendynamo-Prozesse ausgelöst werden
2021	Lotfi Ben-Jaffel u. a.	Erste Entdeckung der Signatur eines Magnetfeldes eines Exoplaneten

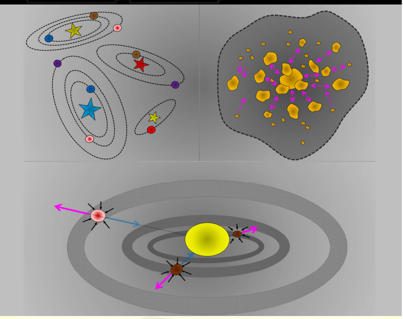
Die Farbkodierung der Schrift kennzeichnet historische Ereignisse im Zusammenhang

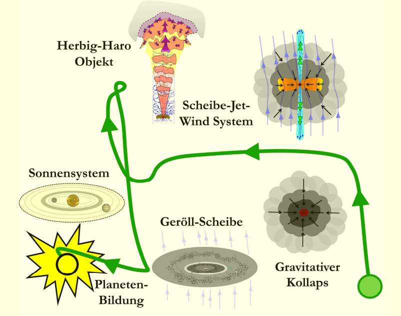
- mit der **Entdeckung des Aufbaus** und der **Entstehung des Sonnensystems**
- mit der **Entdeckung von Magnetfeldern im Sonnensystem**
- mit der **Entwicklung der Scheiben-Jet-Strukturen protostellarer Systeme**

https://ulrich-von-kusserow.de/images/Beitraege/Buecher/Entstehung_Magnetisches_Sonnensystem/Historische_Entdeckungen__Extrasolare_Sternsysteme_Magnetische_Entstehungsprozesse.pdf




Ganymed
Magnetfeldlinien
Magnetfeldachse
Rotationsachse
Jupiter
Sonnenwind
Größe der Sonne - im Vergleich zu den Größen der Magnetosphären der äußeren Planeten
Saturn
Merkur
Erde
Uranus
Neptun

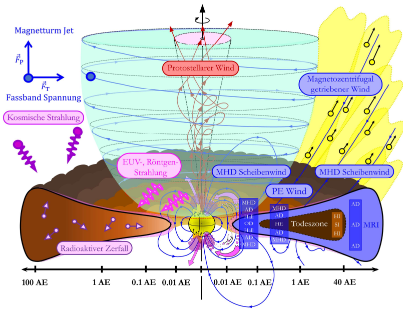


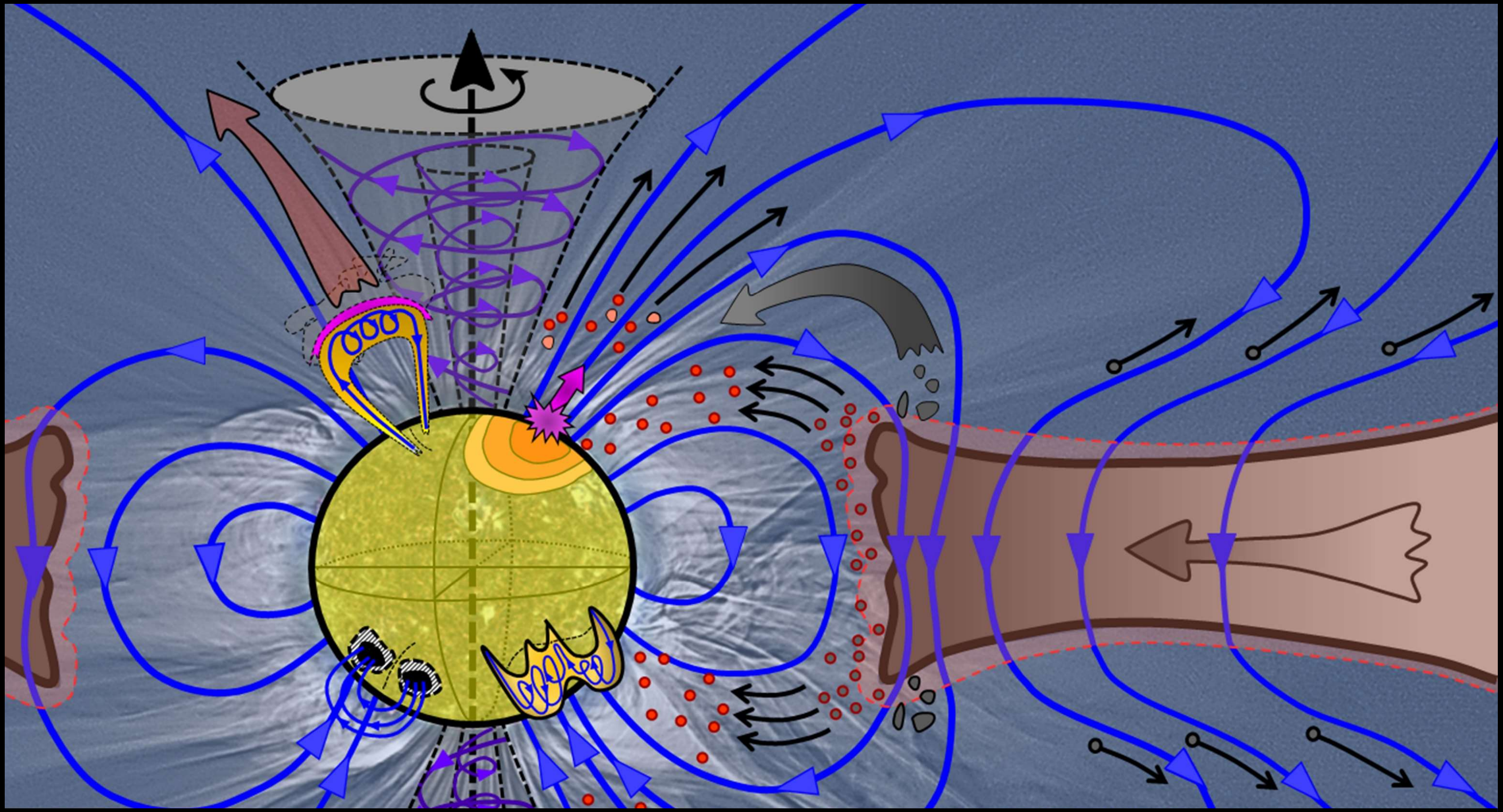

Herbig-Haro Objekt
Scheibe-Jet-Wind System
Sonnensystem
Geröll-Scheibe
Gravitativer Kollaps
Planeten-Bildung

On the Formation of the Magnetic Solar System

Phases of Development History

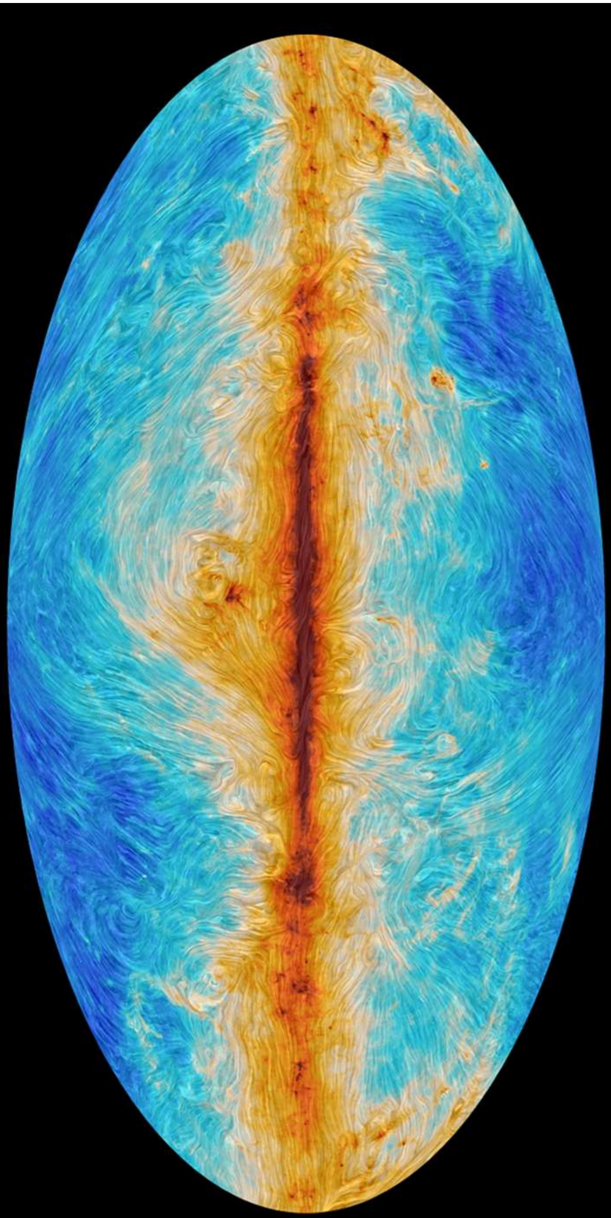
- Structure and dynamics of the heliocentric Solar System — from 1543
  Kopernikus, Galilei, Kepler, Newton, Titius & Bode, Herschel, Le Verrier & Galle
- Discovery of magnetic fields in the Solar System — from 1600
  Gilbert, Hale, Babcock, Pioneer 10
- Early Models of the Formation of the Solar System — from 1630
  Descartes, Swedenborg, Leclerce, Kant, Laplace, …
- Early observations and theories on the development of star systems — from 1852
  Hind, Burnham, Herbig & Haro, Kleinman & Low, Hertzsprung & Russell, Jeans, Hayashi
- Advanced computer-aided analytical modeling — from 1955
- Theories on influence of magnetic fields on the development of star systems — from 1959
  Parker, Mestel, Spitzer, Blandford, Pudritz, Shu, Balbus & Hawley, Wetherill
- Age of discoveries with the HST, VLT, VLA … — from 1990
- Era of sophisticated numerical simulations — from 1990
- Age of discoveries with ALMA, SOFIA, ... — from 2004
- Age of Discovery with the JWST, ELT, SKA, ngVLA, … — from 2022


Magnetturm Jet
$\vec{F}_P$
$\vec{F}_T$
Fassband Spannung
Kosmische Strahlung
Protostellarer Wind
Magnetozentrifugal getriebener Wind
EUV-, Röntgen-Strahlung
MHD Scheibenwind
MHD Scheibenwind
PE Wind
MHD
AD
Hall
OD
HE
Todeszone
HI
SI
MRI
Radioaktiver Zerfall
100 AE
1 AE
0.1 AE
0.01 AE
0.01 AE
0.1 AE
1 AE
40 AE

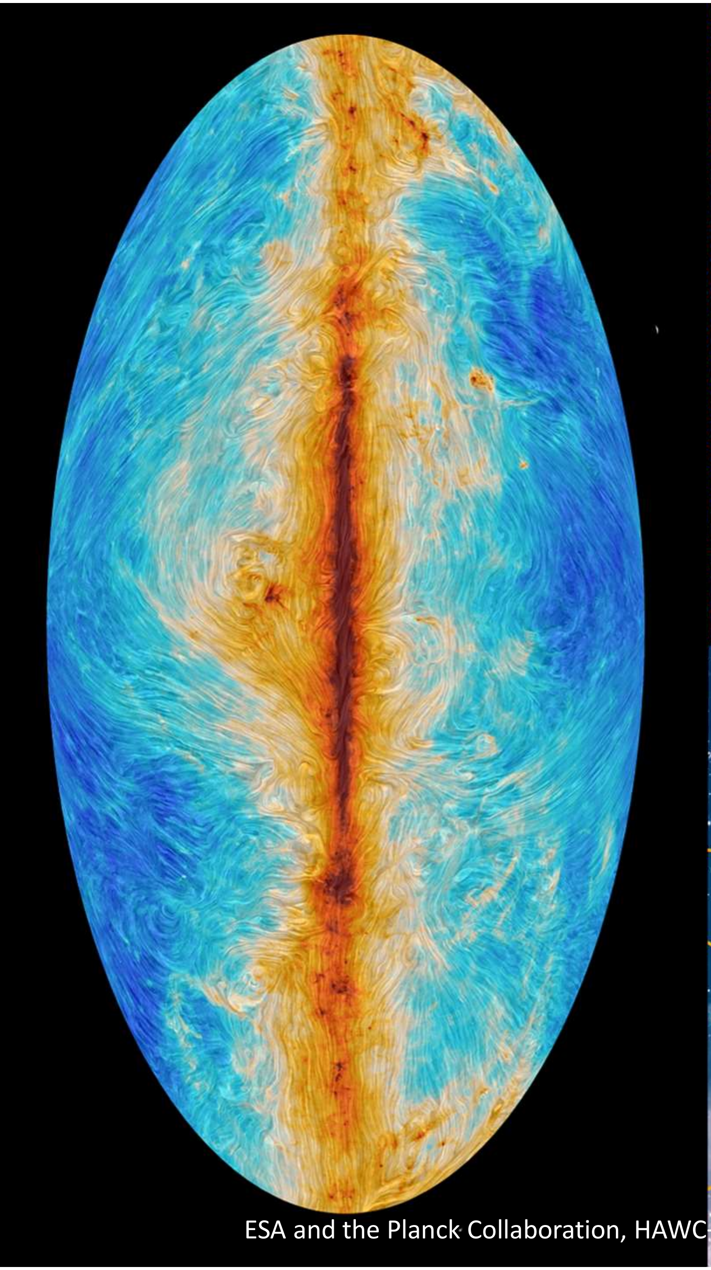


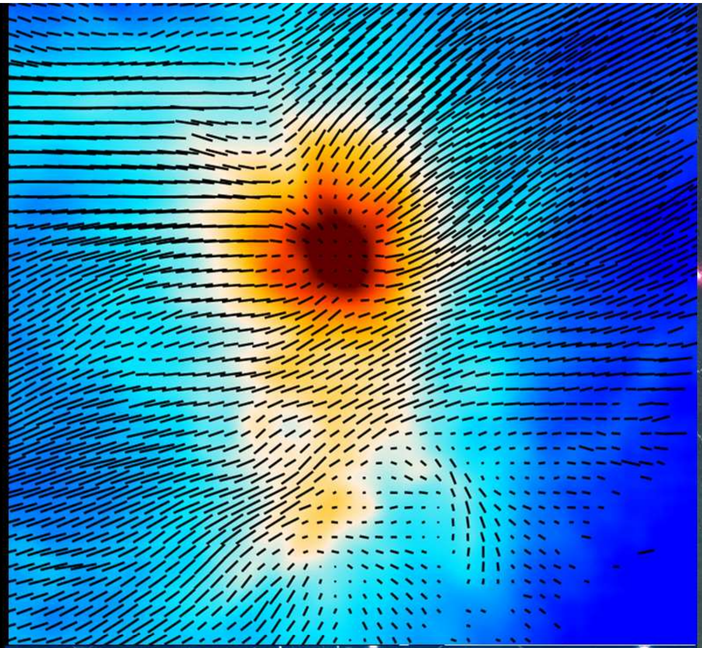
$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{B}) - \vec{\nabla} \times (\eta_{\mathrm{OD}} \cdot \vec{\nabla} \times \vec{B}) + \vec{\nabla} \times \{\eta_{\mathrm{AD}} \cdot (\vec{\nabla} \times \vec{B}) \times \vec{B}\} - \vec{\nabla} \times [\vec{\nabla} \times \{\eta_{\mathrm{HD}} \cdot (\vec{\nabla} \times \vec{B}) \times \vec{B}\}]$$

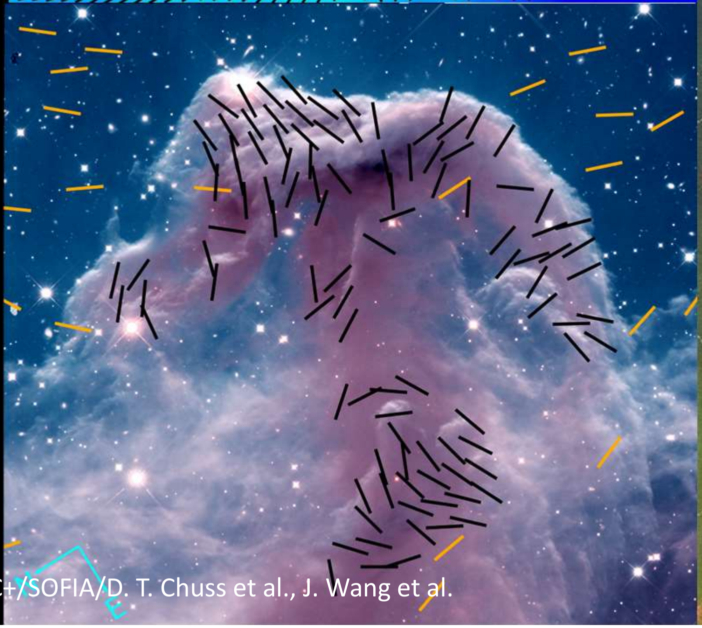
Background Structures



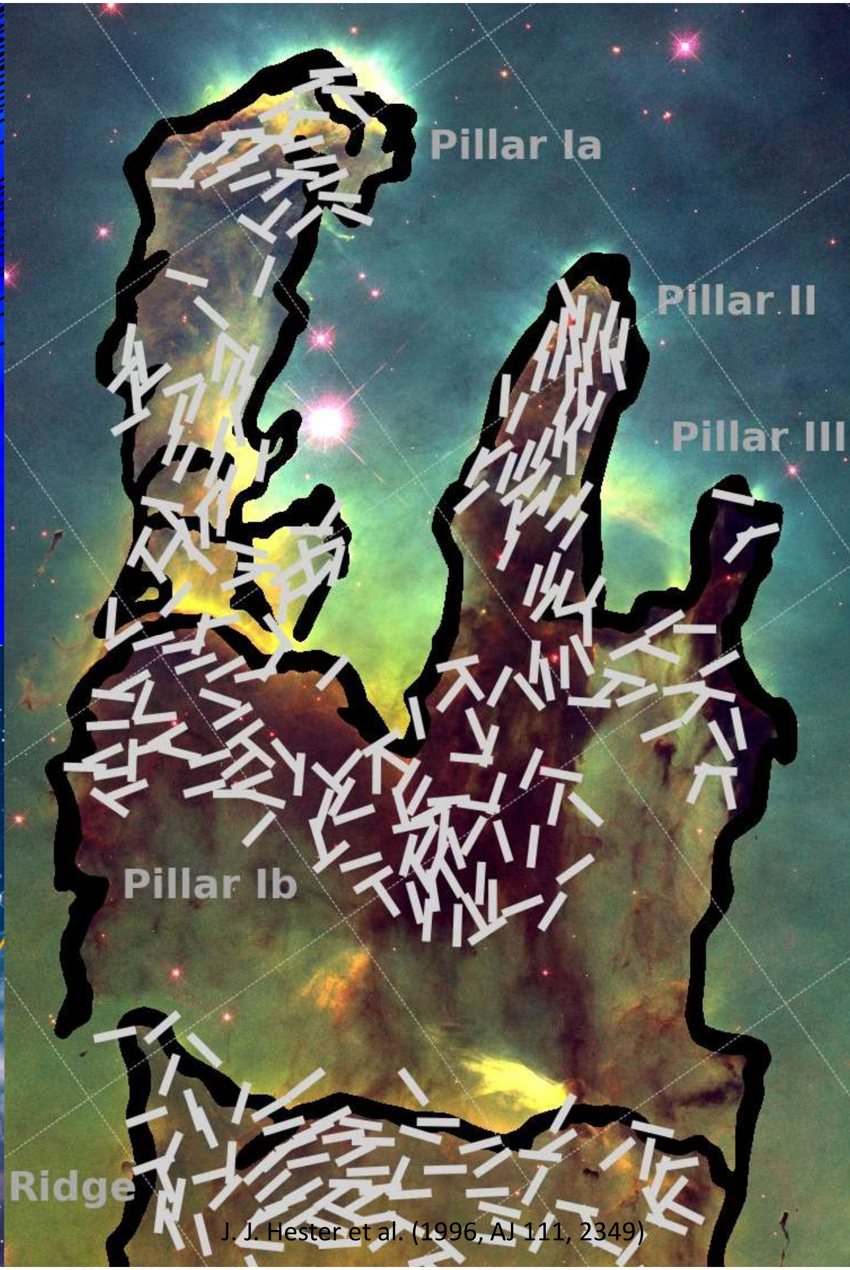
Magnetic fields are likely to direct the gas into orbit around the black hole in the centre of the Milky Way
NASA / SOFIA; NASA / HST



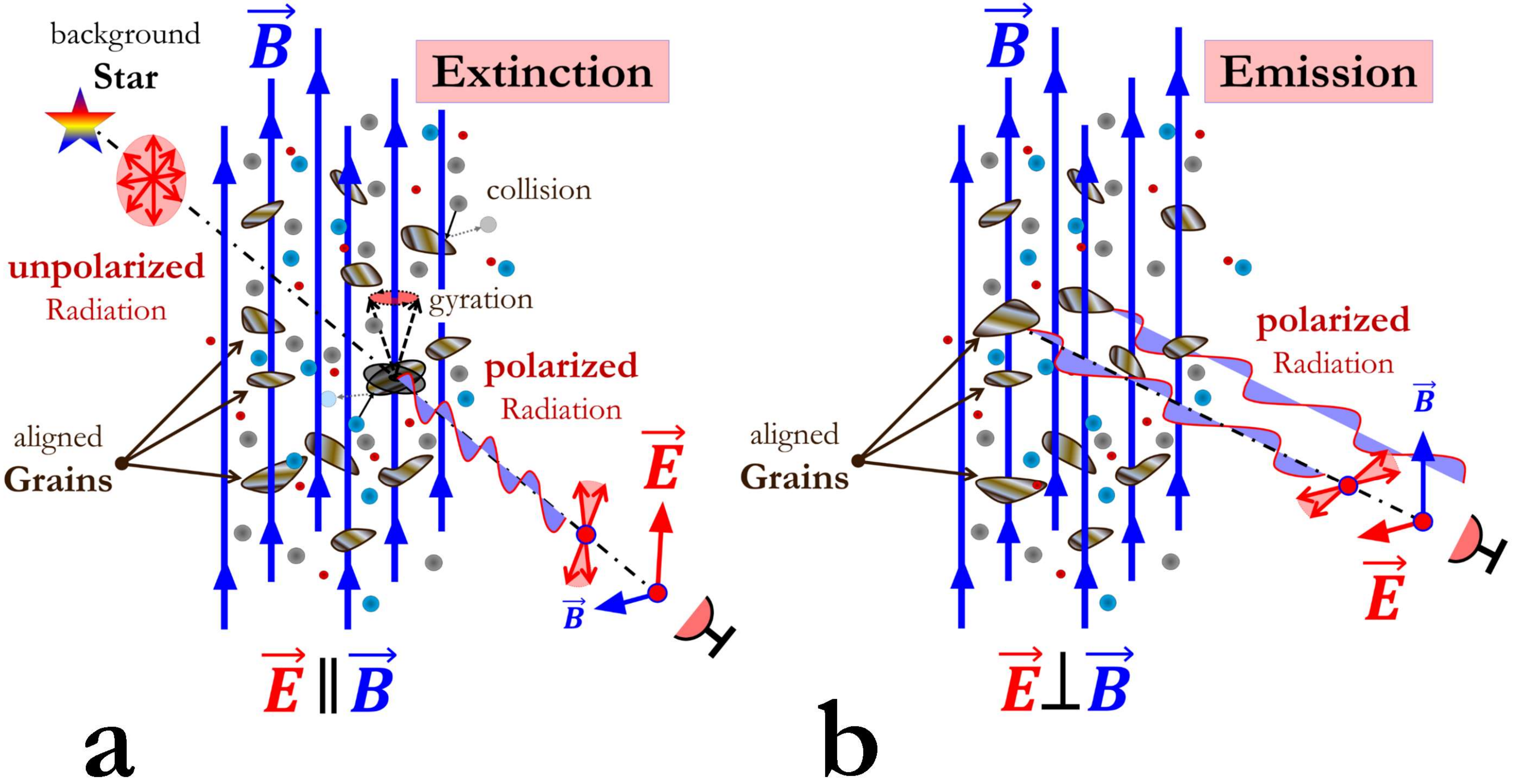




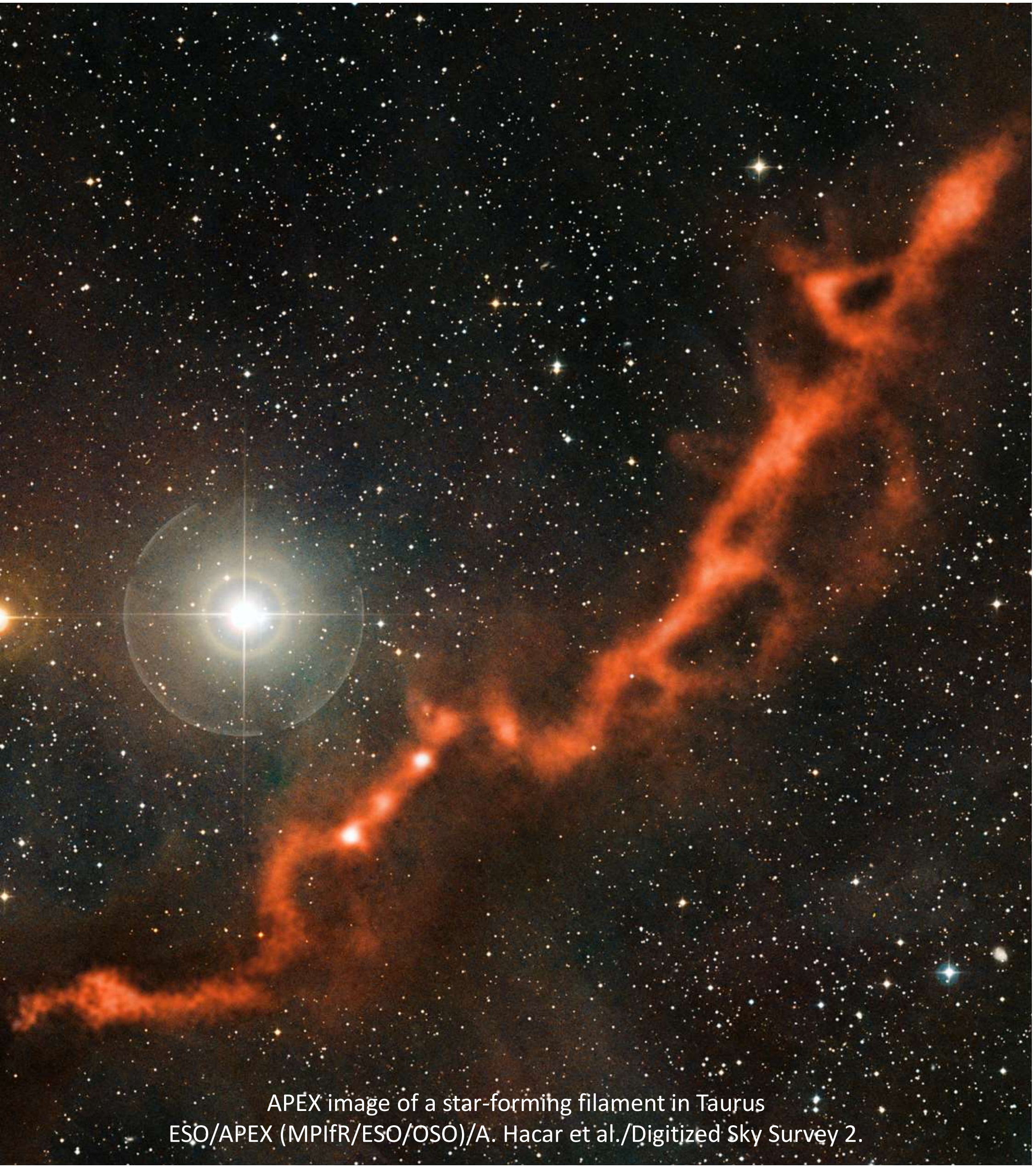
ESA and the Planck Collaboration, HAWC+/SOFIA/D. T. Chuss et al., J. Wang et al.


Pillar Ia
Pillar II
Pillar III
Pillar Ib
Ridge

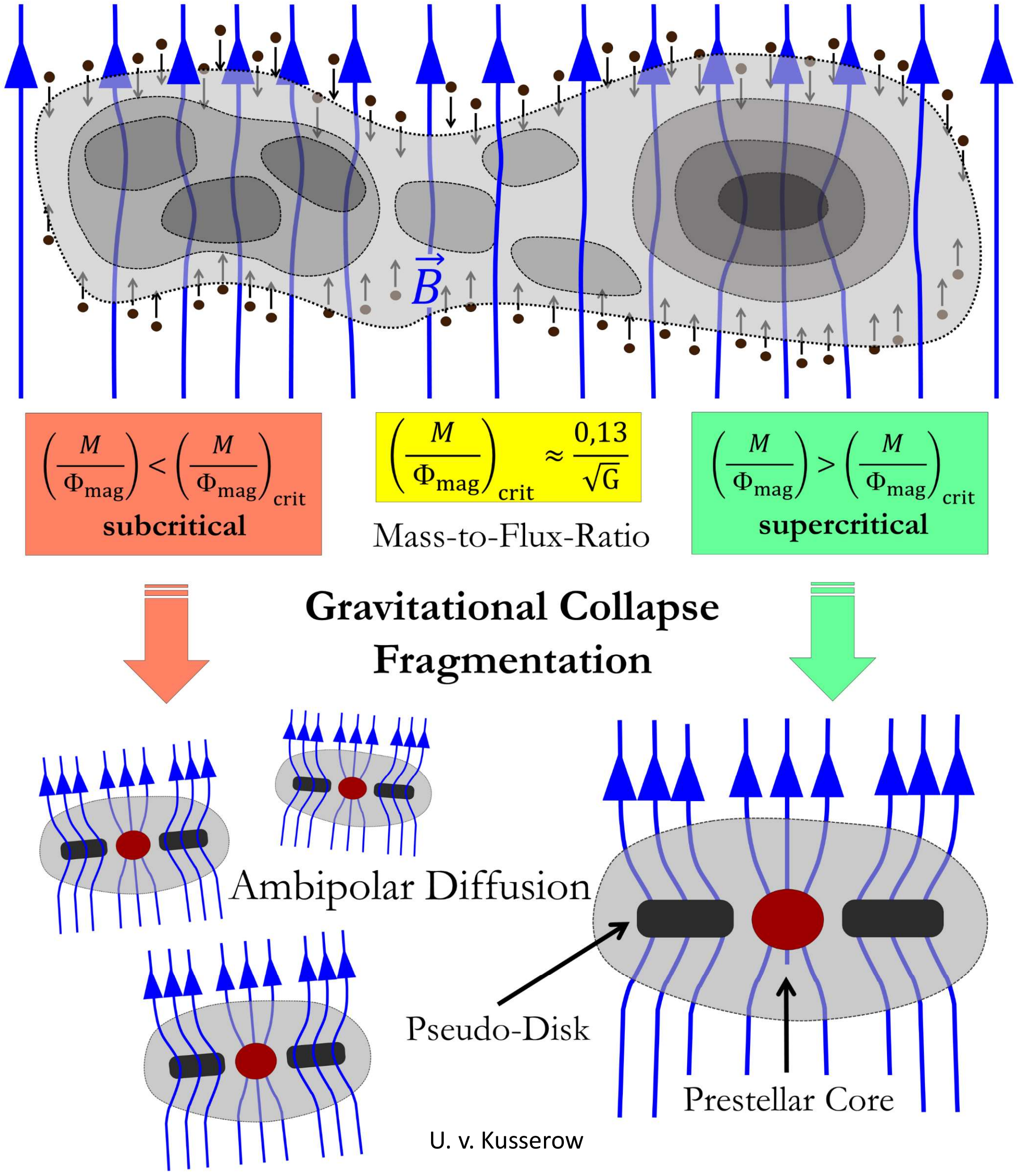
J. J. Hester et al. (1996, AJ 111, 2349)


background
Star
B
Extinction
collision
unpolarized
Radiation
gyration
polarized
Radiation
aligned
Grains
E
B
E ∥ B
a
B
Emission
polarized
Radiation
B
aligned
Grains
E
E ⊥ B
b

Determination of the orientation of interstellar magnetic fields based on the orientation of dust grains using the polarization of the radiation emitted by a star behind them (a) or by asymmetric dust particles themselves (b). - U. v. Kusserow (after A. Lazarian)



APEX image of a star-forming filament in Taurus
ESO/APEX (MPIfR/ESO/OSO)/A. Hacar et al./Digitized Sky Survey 2.



$\vec{B}$

$\left(\frac{M}{\Phi_{mag}}\right) < \left(\frac{M}{\Phi_{mag}}\right)_{crit}$

subcritical

$\left(\frac{M}{\Phi_{mag}}\right)_{crit} \approx \frac{0{,}13}{\sqrt{G}}$

Mass-to-Flux-Ratio

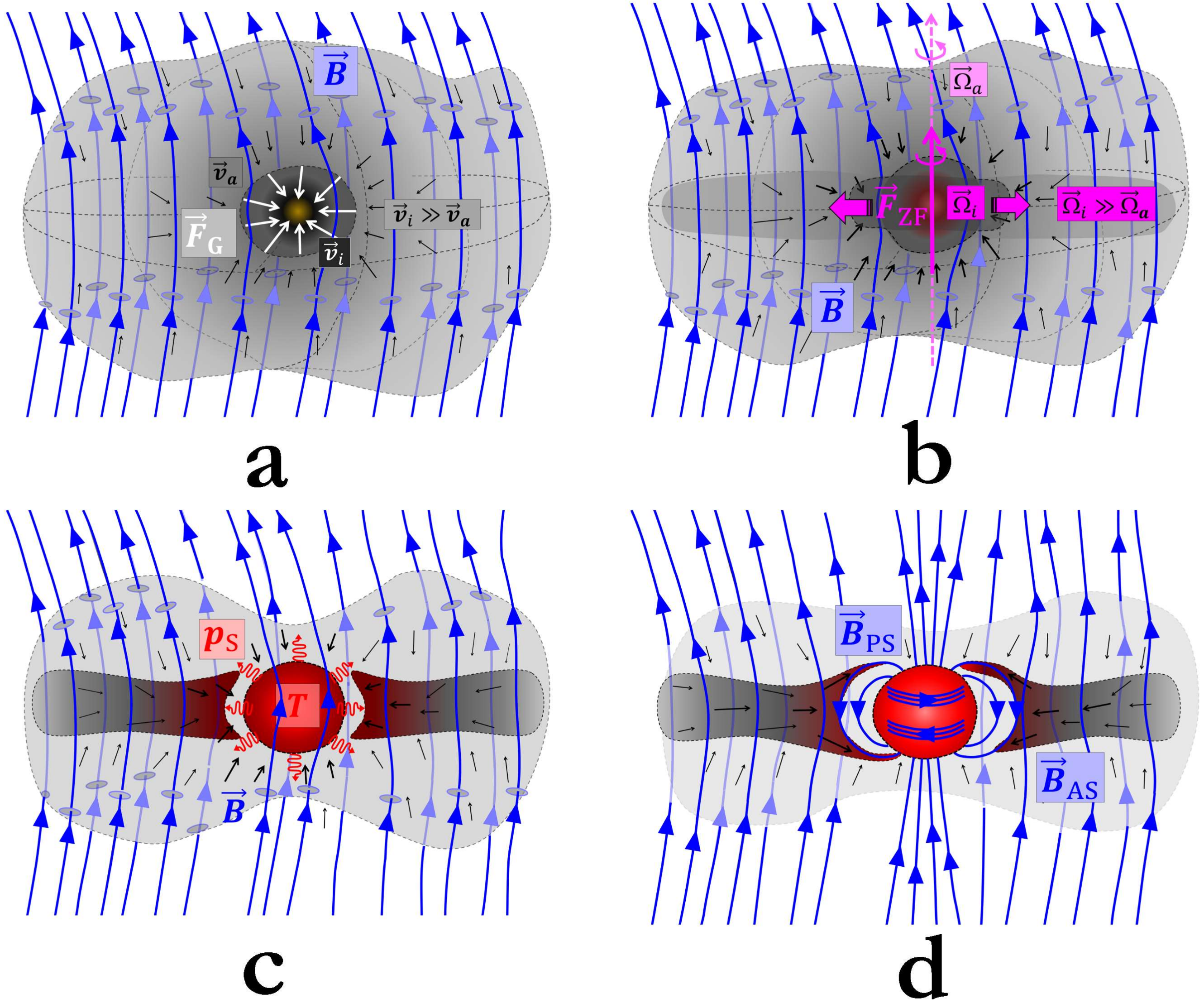
$\left(\frac{M}{\Phi_{mag}}\right) > \left(\frac{M}{\Phi_{mag}}\right)_{crit}$

supercritical

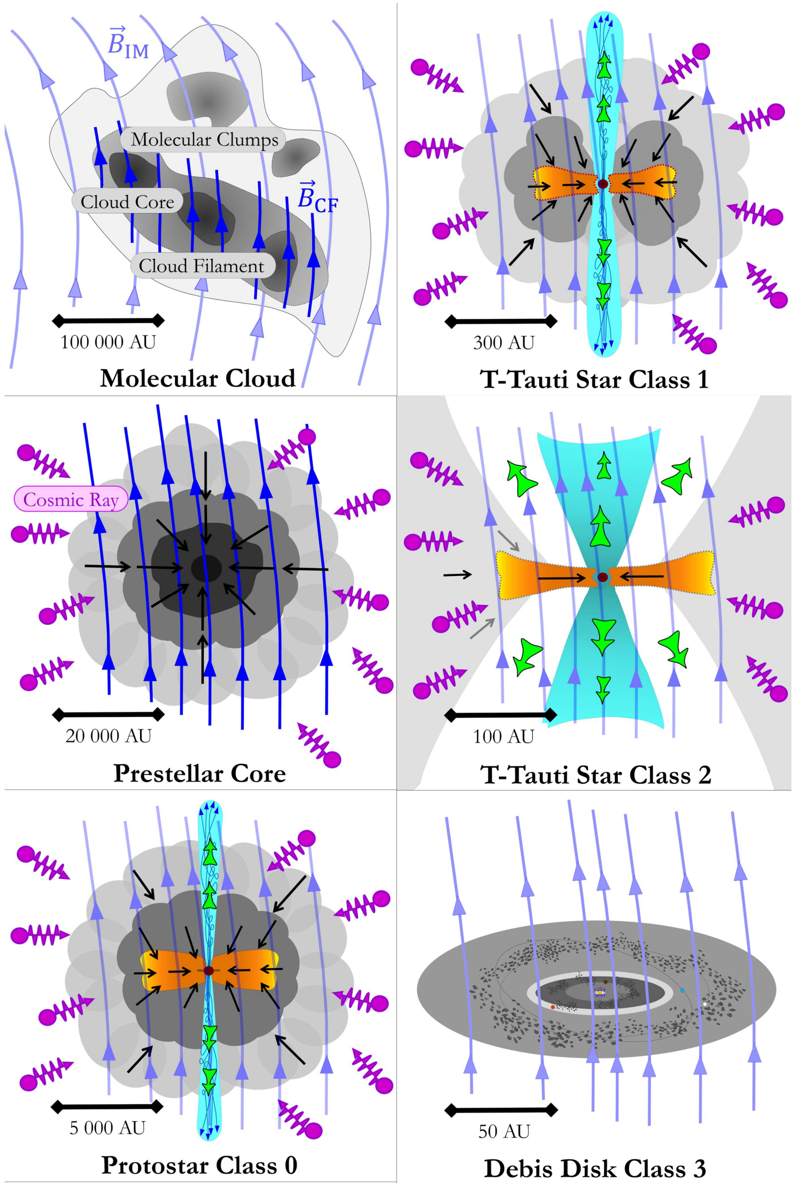
Gravitational Collapse
Fragmentation

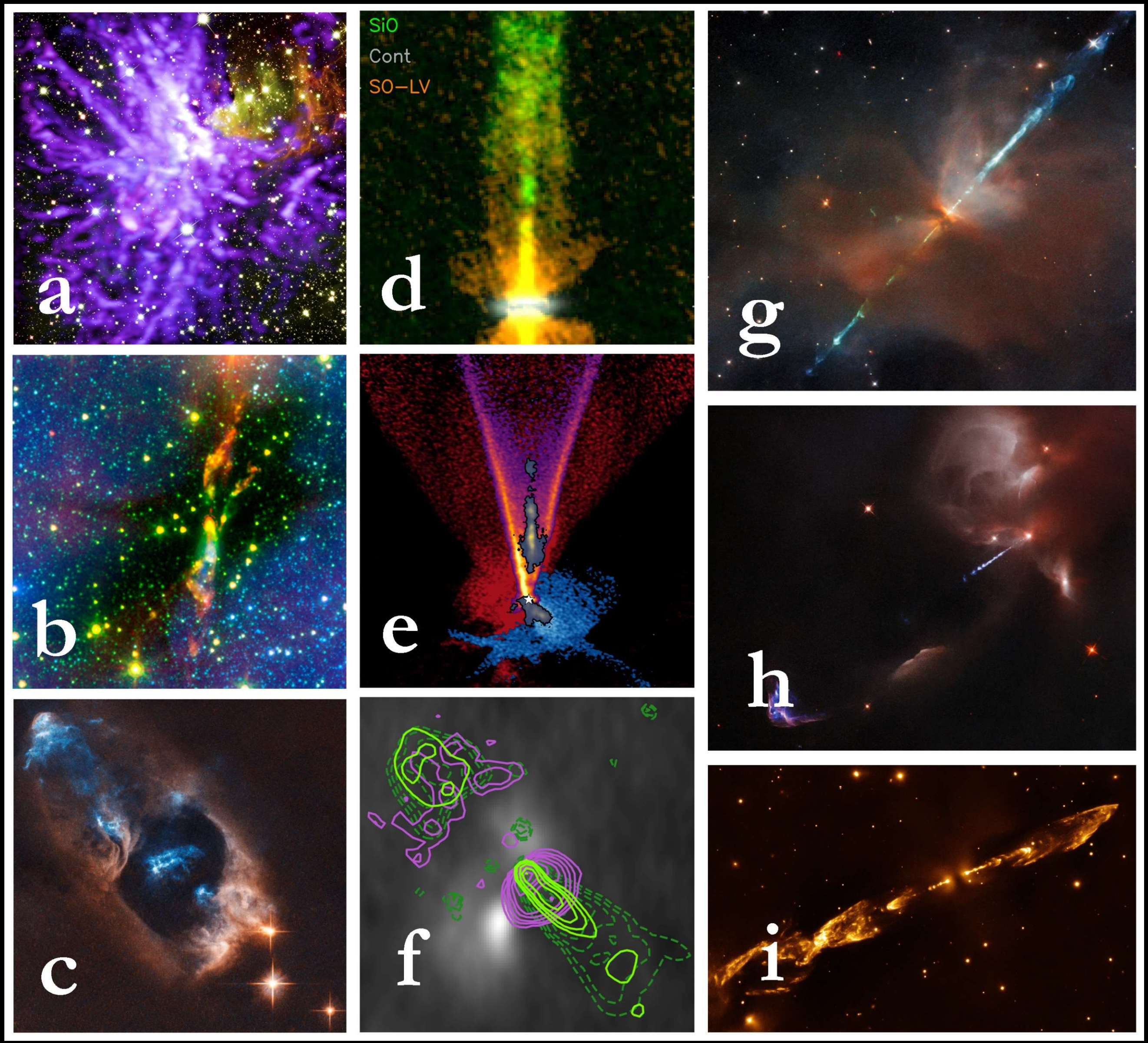
Ambipolar Diffusion
Pseudo-Disk
Prestellar Core

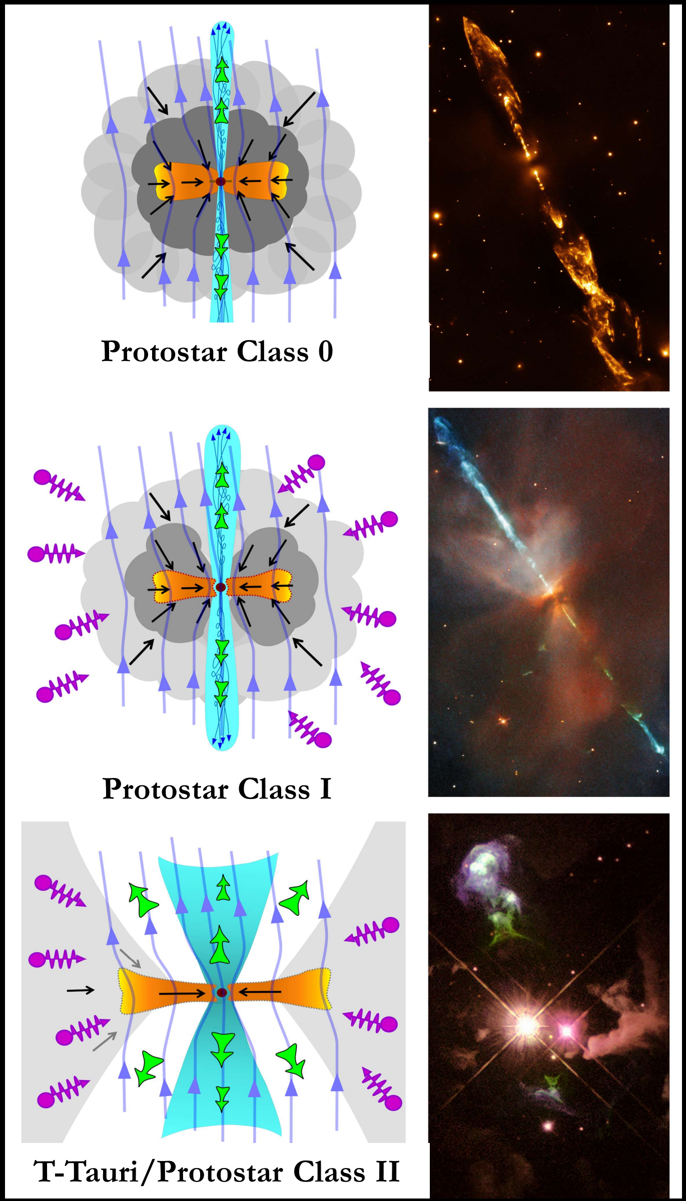
U. v. Kusserow

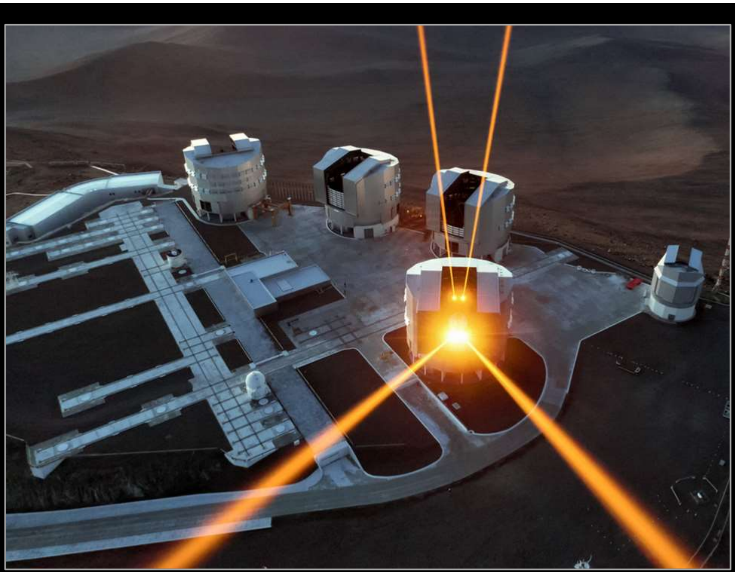

$\vec{B}$
$\vec{v}_a$
$\vec{F}_G$
$\vec{v}_i \gg \vec{v}_a$
$\vec{v}_i$
a
$\vec{\Omega}_a$
$\vec{F}_{ZF}$
$\vec{\Omega}_i$
$\vec{\Omega}_i \gg \vec{\Omega}_a$
$\vec{B}$
b
p_S
T
$\vec{B}$
c
$\vec{B}_{PS}$
$\vec{B}_{AS}$
d

Evolution of Prestellar Cores and Protostars, Pseudodisks and Accretion Disks in a Magnetized Molecular Cloud
U. v. Kusserow


$\vec{B}_{IM}$
Molecular Clumps
Cloud Core
$\vec{B}_{CF}$
Cloud Filament
100 000 AU
Molecular Cloud
300 AU
T-Tauti Star Class 1
Cosmic Ray
20 000 AU
Prestellar Core
100 AU
T-Tauti Star Class 2
5 000 AU
Protostar Class 0
50 AU
Debis Disk Class 3


a
SiO
Cont
SO–LV
d
g
b
e
h
c
f
i


Protostar Class 0
Protostar Class I
T-Tauri/Protostar Class II



Very Large Telescope (VLT) ESO

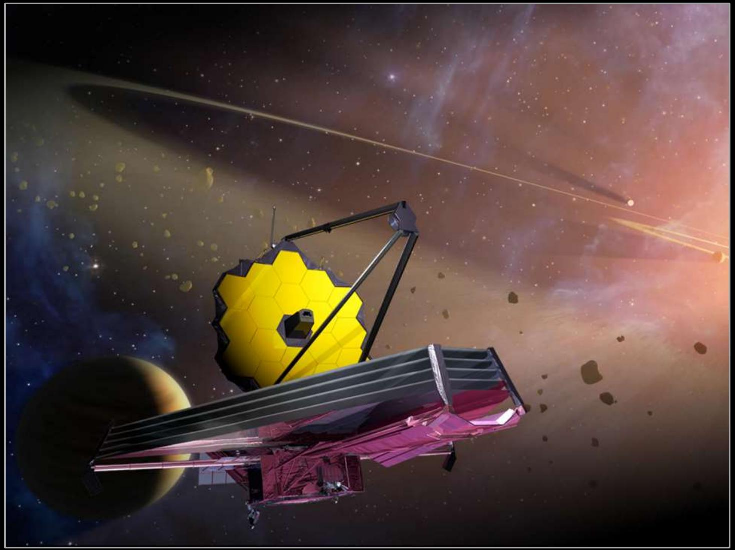
SOFIA
NASA
DLR

Stratospheric Observatory for Infrared Astronomy (SOFIA)

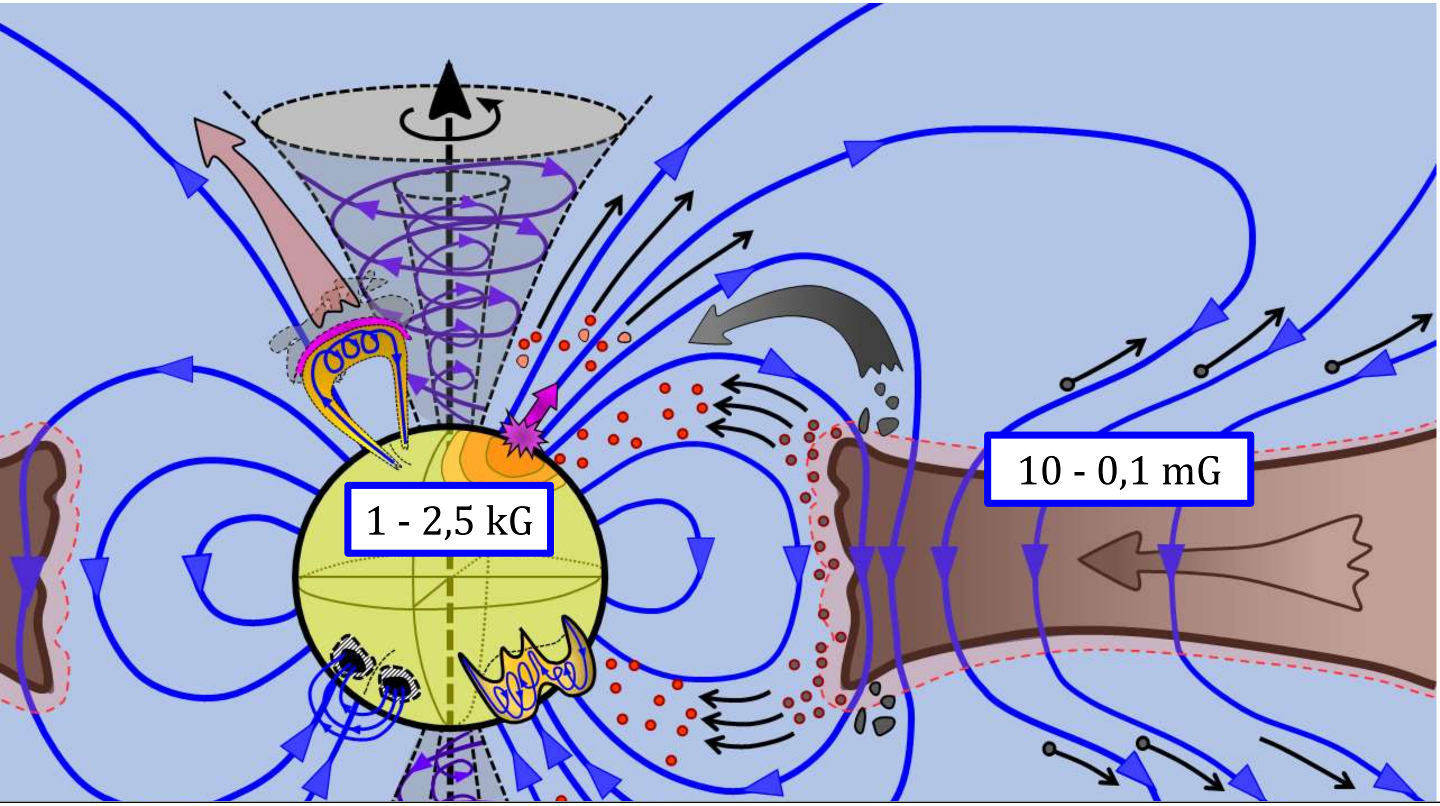
Hubble Space Telescope (HST) NASA

European Large Telescope (ELT) ESO

Atacama Large Millimeter/submillimeter Array (ALMA) ESO



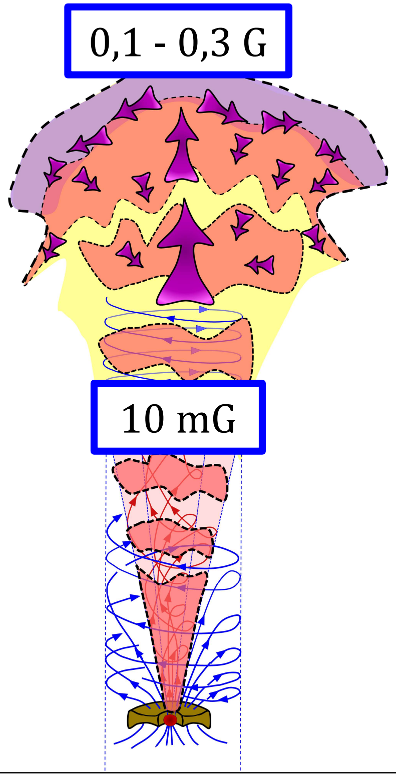
James Webb Space Telescope (JWST) NASA

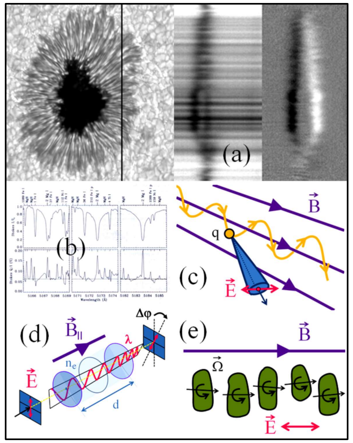


0,1 - 10^3 μG

$B \propto \rho^{2/3}$

$B \propto \rho^{1/2}$





Determination of the Magnetic Flux Density $\vec{B}$

(strength, orientation, direction)

- Zeeman effect splitting
- Stokes parameter
- Synchrotron radiation
- Faraday rotation
- Polarization of dust emission
- Polarization of starlight (dust quenching)

Component in the line of sight to the observer (B_{LOS})

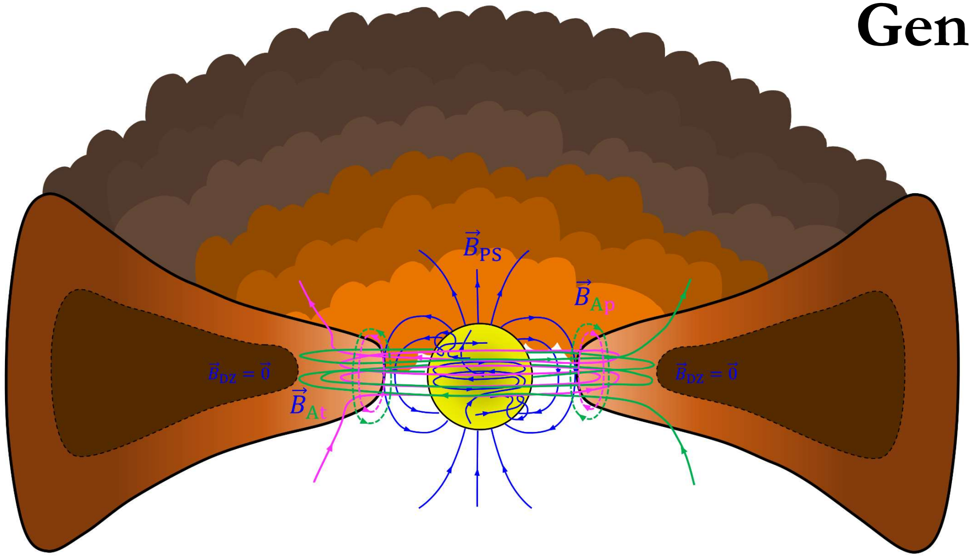
Component in the plane of the sky (B_{POS})

Galactic magnetic field models

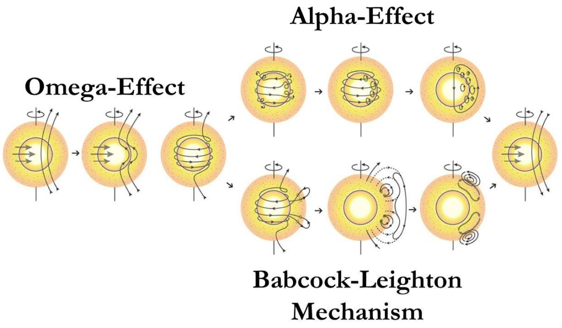
- Hanle effect
- Ion-to-neutral linewidth ratio
- Atomic alignmentRatio of perpendicular to parallel velocity fluctuations

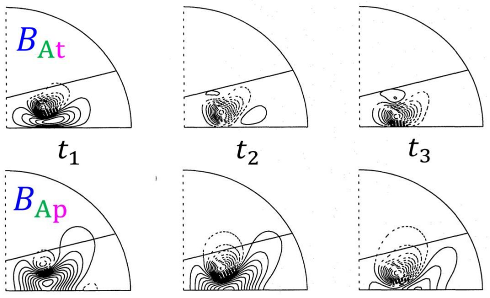
U. v. Kusserow

Generation and Transport of Magnetic Fields


$\vec{B}_{\mathrm{PS}}$
$\vec{B}_{\mathrm{Ap}}$
$\vec{B}_{\mathrm{DZ}} = \vec{0}$
$\vec{B}_{\mathrm{DZ}} = \vec{0}$
$\vec{B}_{\mathrm{At}}$

- Generation of galactic magnetic fields by the **Bierman battery effect (1)**
- Existence of **magnetic seed fields** in molecular clouds
- **Dynamo processes (2)** in **prestellar cores** and **protostars (2)**
- **Accretion disk dynamo** processes **(2)**
- Magnetic field transport in **accretion disks** and protostellar **wind systems (3)**
- Dynamo processes in **protoplanets**
- Dynamo processes in **protomoons**


Alpha-Effect
Omega-Effect
Babcock-Leighton Mechanism



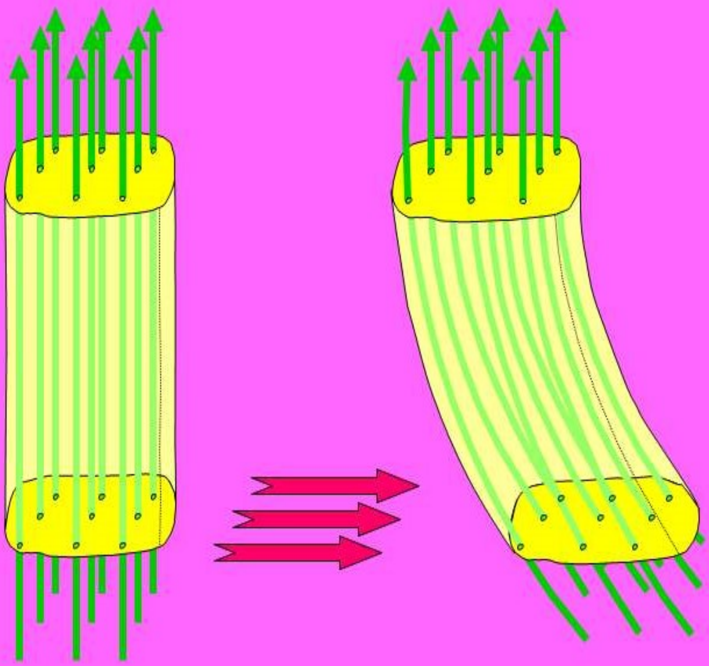
(1)
$$\frac{\partial \vec{B}}{\partial t} = \frac{\mathrm{m_H}}{2\,\mathrm{e}} \cdot \frac{\vec{\nabla} p \times \vec{\nabla} \rho}{\rho^2}$$

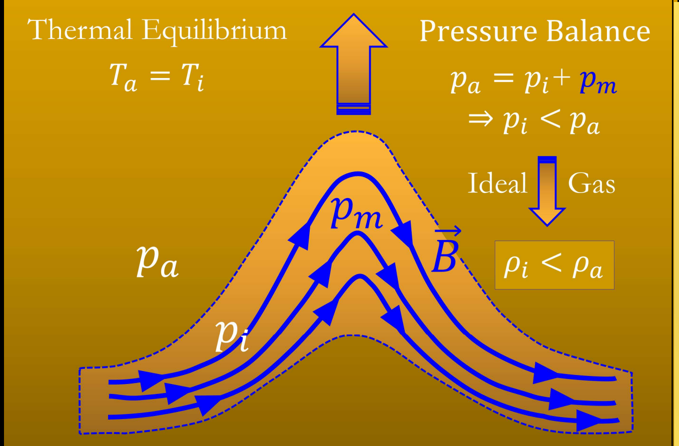
(2)
$$\frac{\partial \vec{B}}{\partial t} = \underbrace{\vec{\nabla} \times \left(\vec{v} \times \vec{B}\right)}_{\omega\text{ - Effect}} + \underbrace{\vec{\nabla} \times \left(\alpha \cdot \vec{B}\right)}_{\alpha\text{ - Effect}} + \underbrace{\eta \cdot \vec{\nabla}^2 \vec{B}}_{\text{Diffusion-Term}}$$

(3)
$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left[\vec{v} \times \vec{B} - \eta_{\mathrm{OR}} \vec{\nabla} \times \vec{B} - \eta_{\mathrm{HE}} \left(\vec{\nabla} \times \vec{B}\right) \times \vec{B} - \eta_{\mathrm{AD}} \left(\left(\vec{\nabla} \times \vec{B}\right) \times \vec{B}\right) \times \vec{B}\right]$$

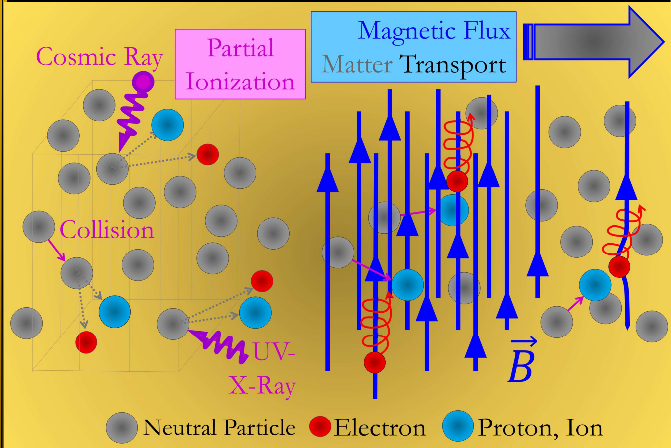
U. v. Kusserow, S. Sanchez/A. Fournier/J. Aubert, U. Torkelsson/A. Brandenburg

Model image of
“Frozen” in Magnetic Field Lines

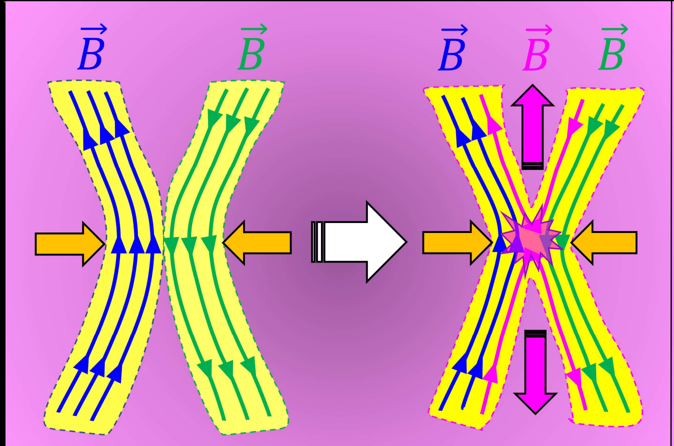



Thermal Equilibrium
$T_a = T_i$
Pressure Balance
$p_a = p_i + p_m$
$\Rightarrow p_i < p_a$
Ideal Gas
$\rho_i < \rho_a$
p_m
$\vec{B}$
p_a
p_i

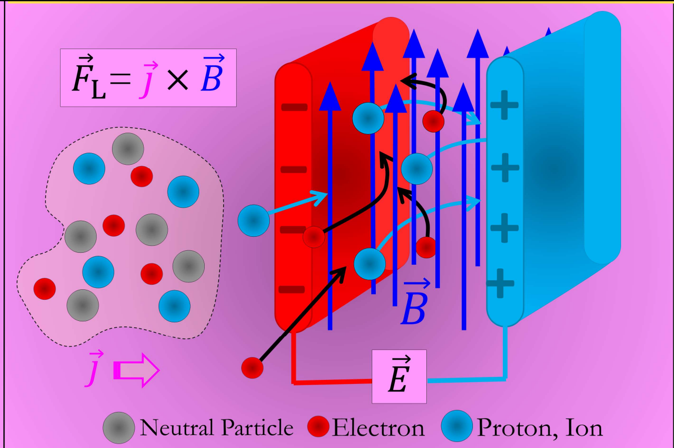
Magnetic Bouyancy


Cosmic Ray
Partial Ionization
Magnetic Flux
Matter Transport
Collision
UV-
X-Ray
$\vec{B}$
Neutral Particle
Electron
Proton, Ion

Ambipolar Diffusion

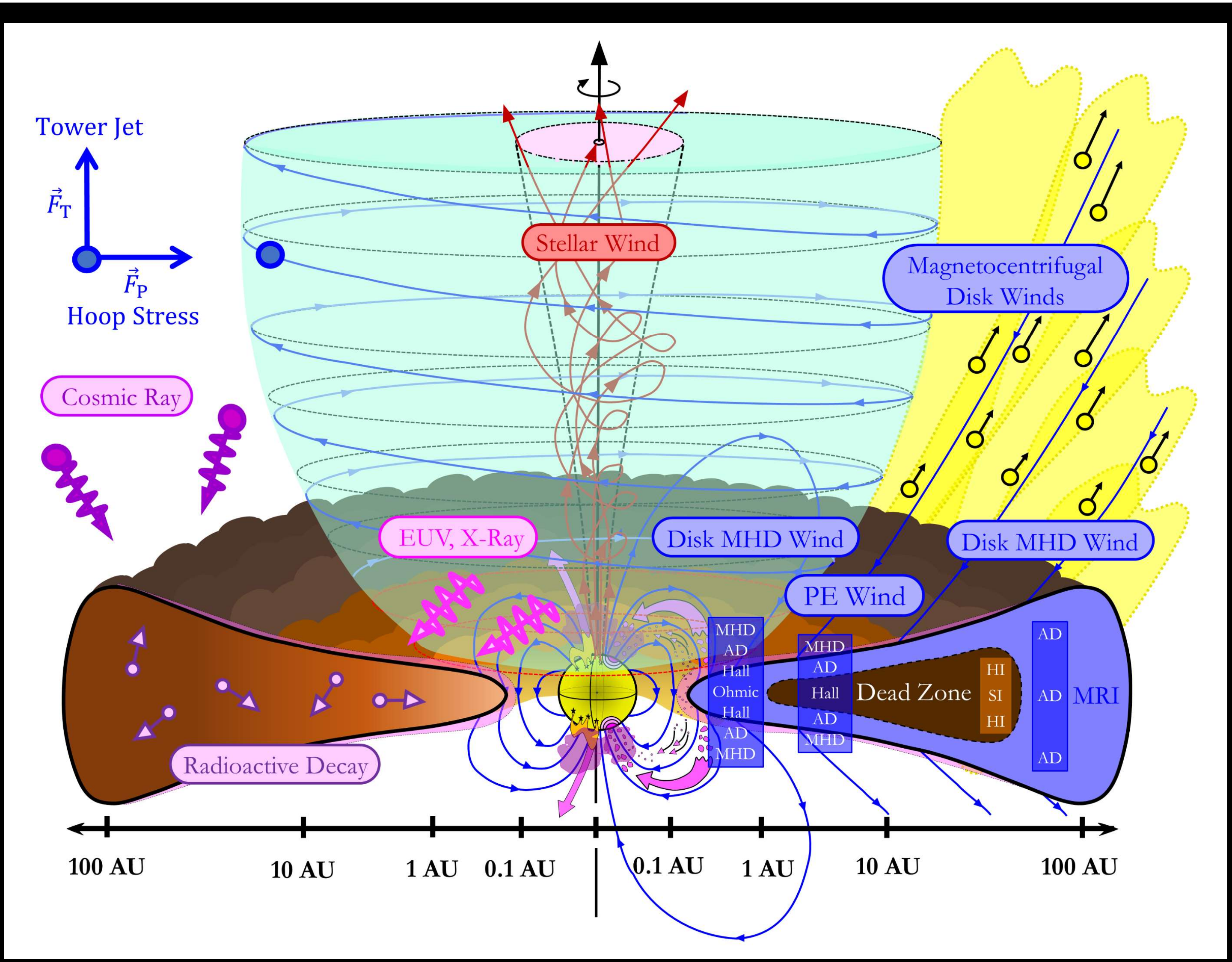

$\vec{B}$
$\vec{B}$
$\vec{B}$
$\vec{B}$
$\vec{B}$

Magnetic Reconnection


$\vec{F}_L = \vec{j} \times \vec{B}$
$\vec{j}$
$\vec{B}$
$\vec{E}$
Neutral Particle
Electron
Proton, Ion

Hall Effect

U. v. Kusserow

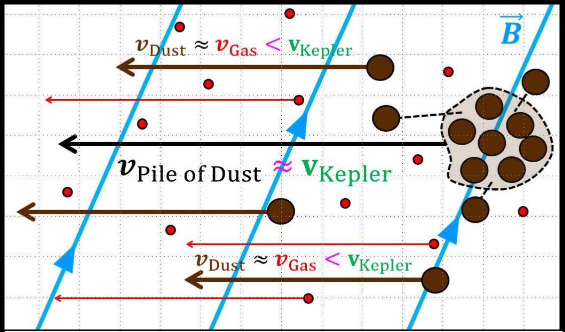

Tower Jet
$\vec{F}_T$
$\vec{F}_P$
Hoop Stress
Stellar Wind
Magnetocentrifugal Disk Winds
Cosmic Ray
EUV, X-Ray
Disk MHD Wind
Disk MHD Wind
PE Wind
MHD
AD
Hall
Ohmic
Hall
AD
MHD
MHD
AD
Hall
AD
MHD
Dead Zone
HI
SI
HI
AD
AD
AD
MRI
Radioactive Decay
100 AU
10 AU
1 AU
0.1 AU
0.1 AU
1 AU
10 AU
100 AU

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla}\times(\vec{v}\times\vec{B}) - \vec{\nabla}\times(\eta_{OD}\cdot\vec{\nabla}\times\vec{B}) + \vec{\nabla}\times\{\eta_{AD}\cdot(\vec{\nabla}\times\vec{B})\times\vec{B}\} - \vec{\nabla}\times[\vec{\nabla}\times\{\eta_{HD}\cdot(\vec{\nabla}\times\vec{B})\times\vec{B}\}]$$

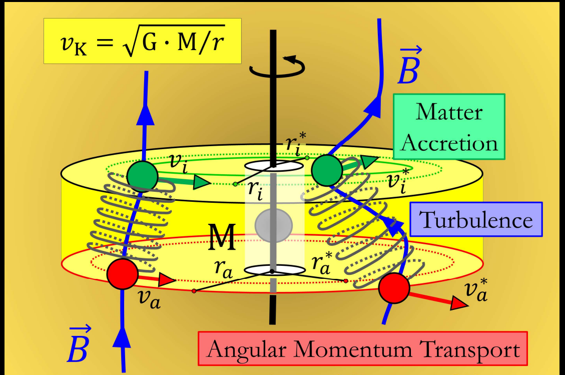
U. v. Kusserow/C. Fendt

Angular Momentum Transport Processes in Star Formation

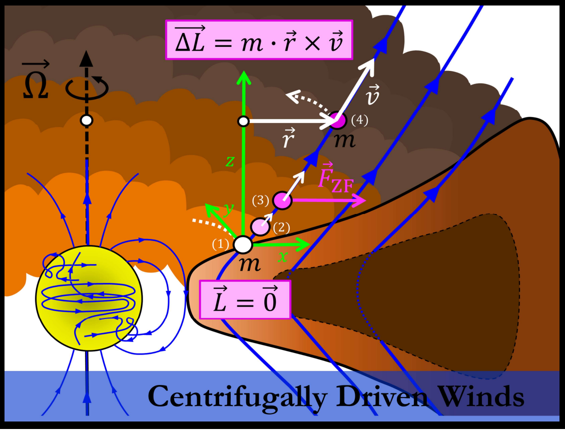
- Angular momentum exchange due to the passage of star formation regions through the galactic spiral arms
- Angular momentum exchange between by collisions of molecular and dust clouds
- Angular momentum exchange between prestellar cores/pseudodisks and the surrounding clouds, rotating with different speeds
- Removel of angular momentum by magnetohydrodynamic Alfvén-waves after the generation of magnetic fields
- Angular momentum exchange between gas and dust particles (streaming instability)
- Angular momentum transport due to friction processes, hydrodynamic instabilities and the magnetorotational instability (MRI) in accretion disks
- Removal of angular momentum in magnetized protostellar and disk winds
- Migration processes due to angular momentum exchange between gas particles, pebbles, planetesimals and protoplanets and the accretion disk
- Angular momentum transfer through contact between the accretion disk and the molecular clouds bordering it
- Angular momentum input through streamers flowing into the protoplanetary disk from outside
- Effective angular momentum removal from the magnetosphere of the young pre-main sequence star by continuous magnetized stellar wind and coronal mass ejections
- Angular momentum transport in young multiple star systems


$v_{\text{Dust}} \approx v_{\text{Gas}} < \text{v}_{\text{Kepler}}$
$\vec{B}$
$v_{\text{Pile of Dust}} \approx \text{v}_{\text{Kepler}}$
$v_{\text{Dust}} \approx v_{\text{Gas}} < \text{v}_{\text{Kepler}}$

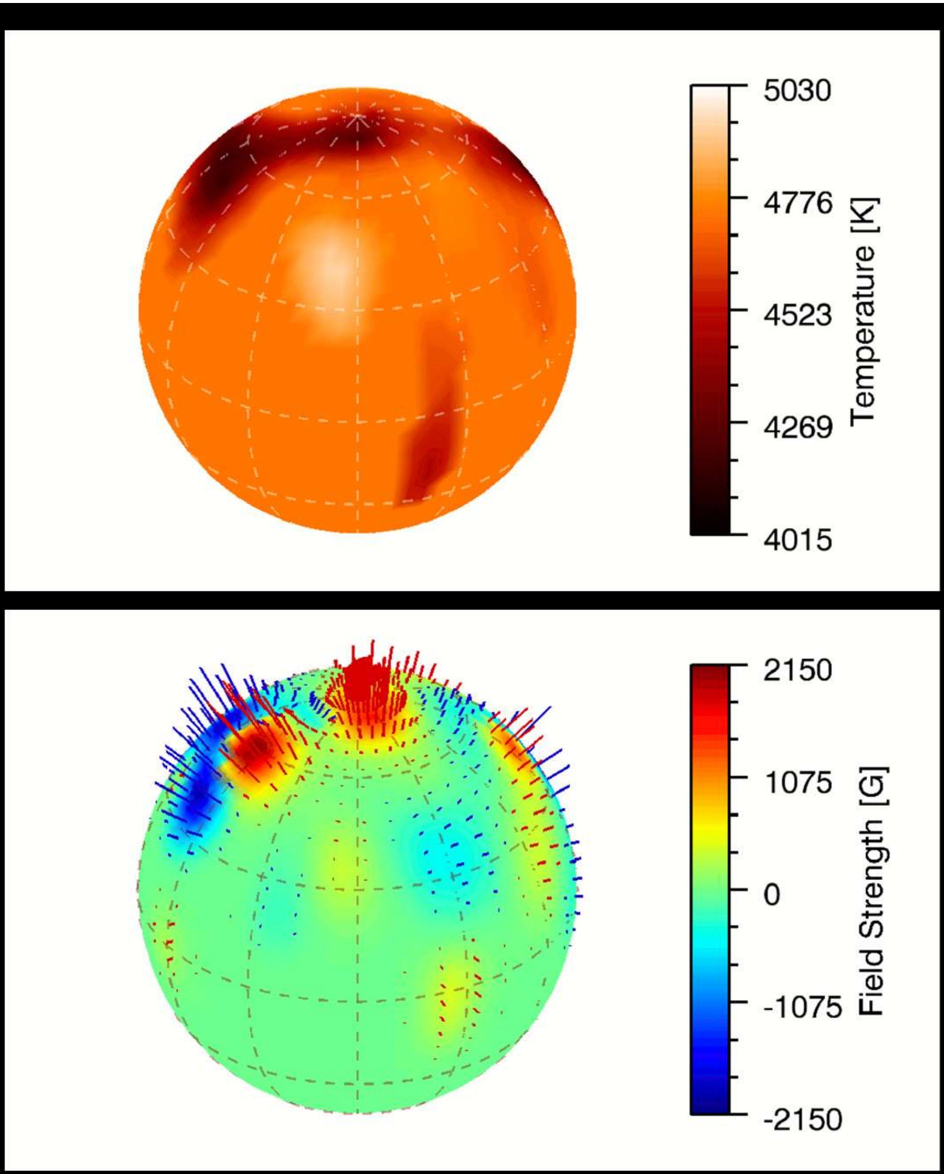
Streaming Instability


$v_{\text{K}} = \sqrt{\text{G} \cdot \text{M}/r}$
$\vec{B}$
Matter Accretion
r_i^*
v_i
r_i
v_i^*
Turbulence
M
r_a
r_a^*
v_a
v_a^*
$\vec{B}$
Angular Momentum Transport

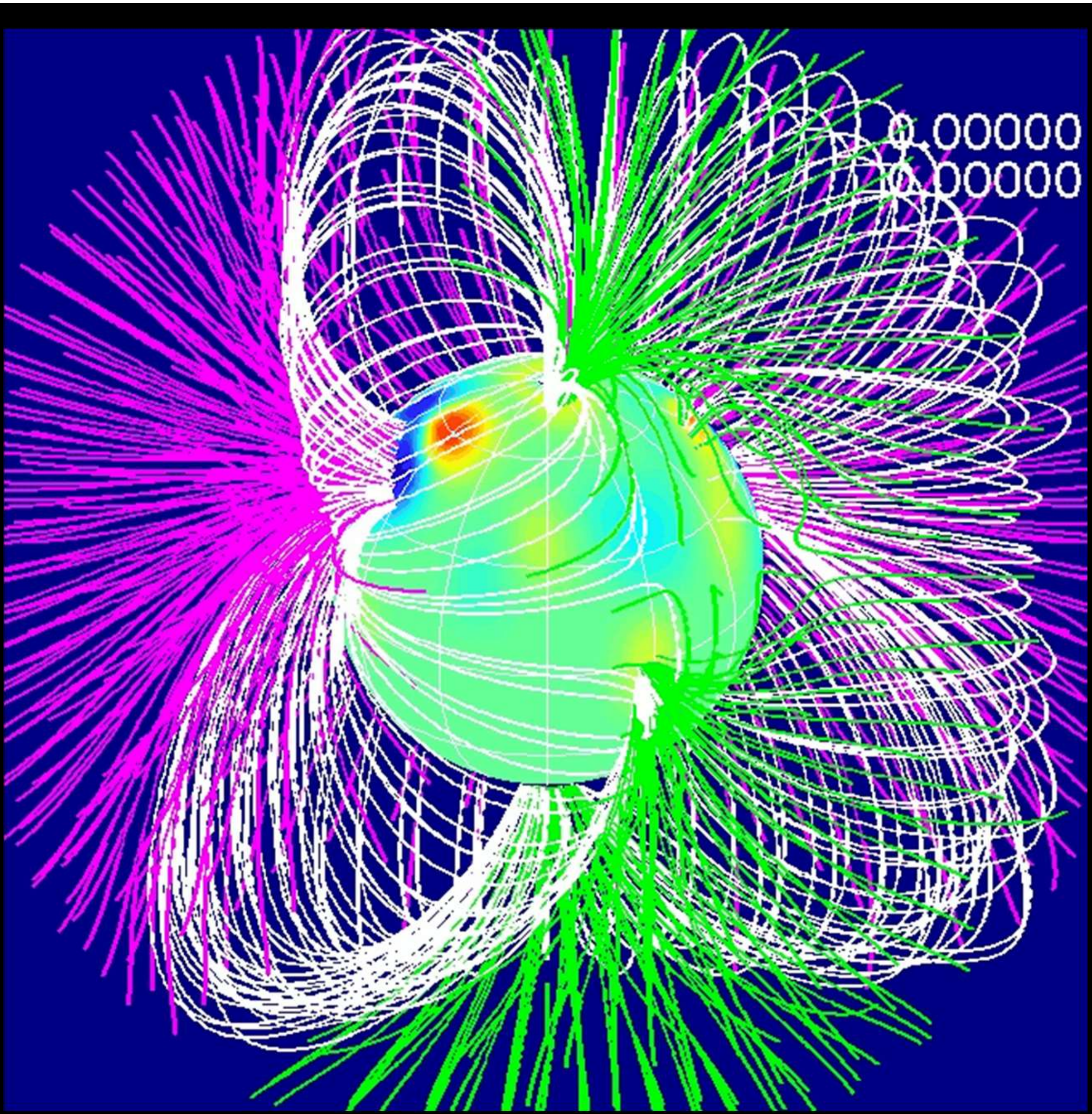
Magnetorotational Instability


$\overrightarrow{\Delta L} = m \cdot \vec{r} \times \vec{v}$
$\vec{\Omega}$
$\vec{v}$
(4)
$\vec{r}$
m
z
$\vec{F}_{\text{ZF}}$
(3)
y
(2)
(1)
x
m
$\vec{L} = \vec{0}$

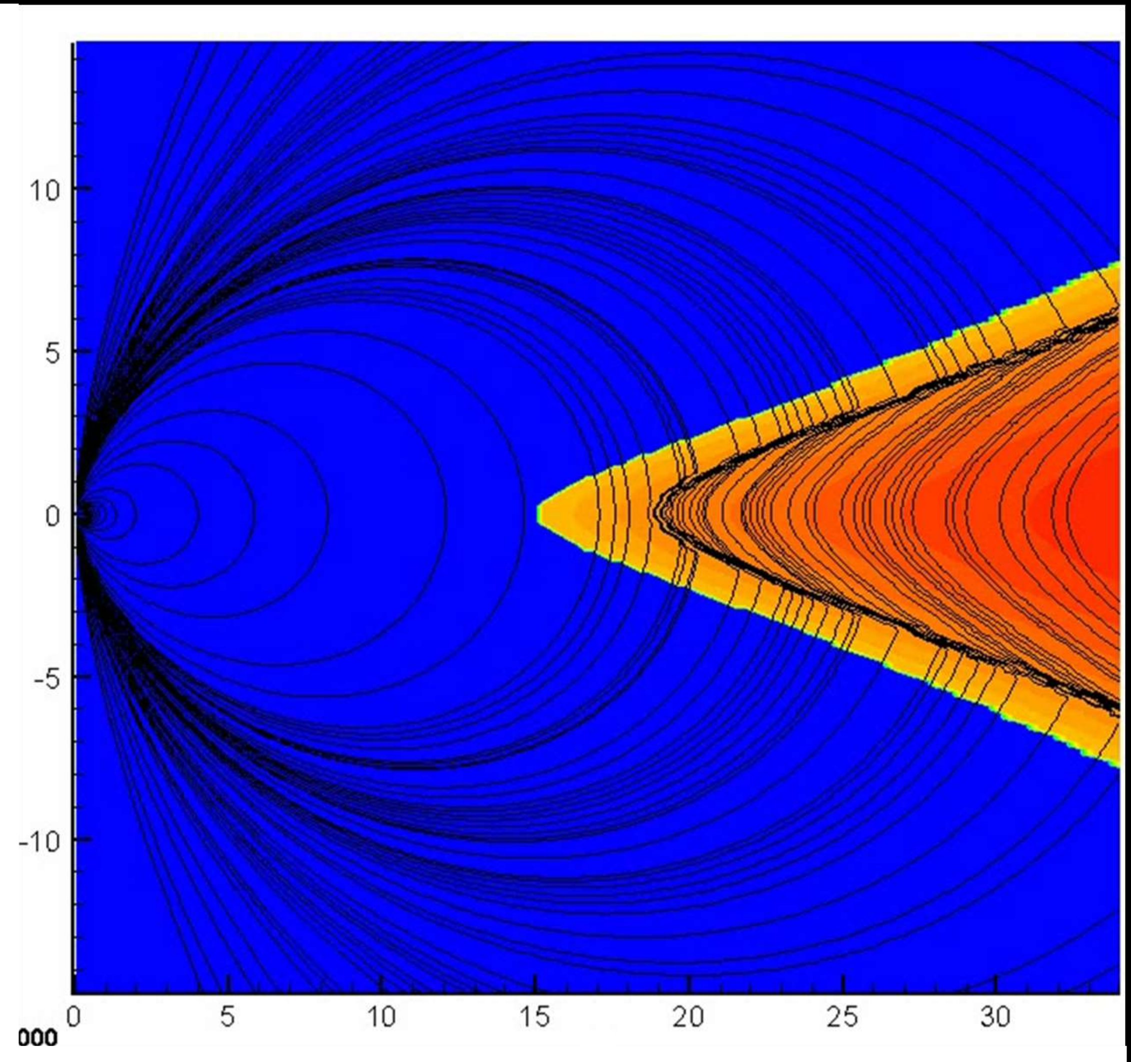
Centrifugally Driven Winds



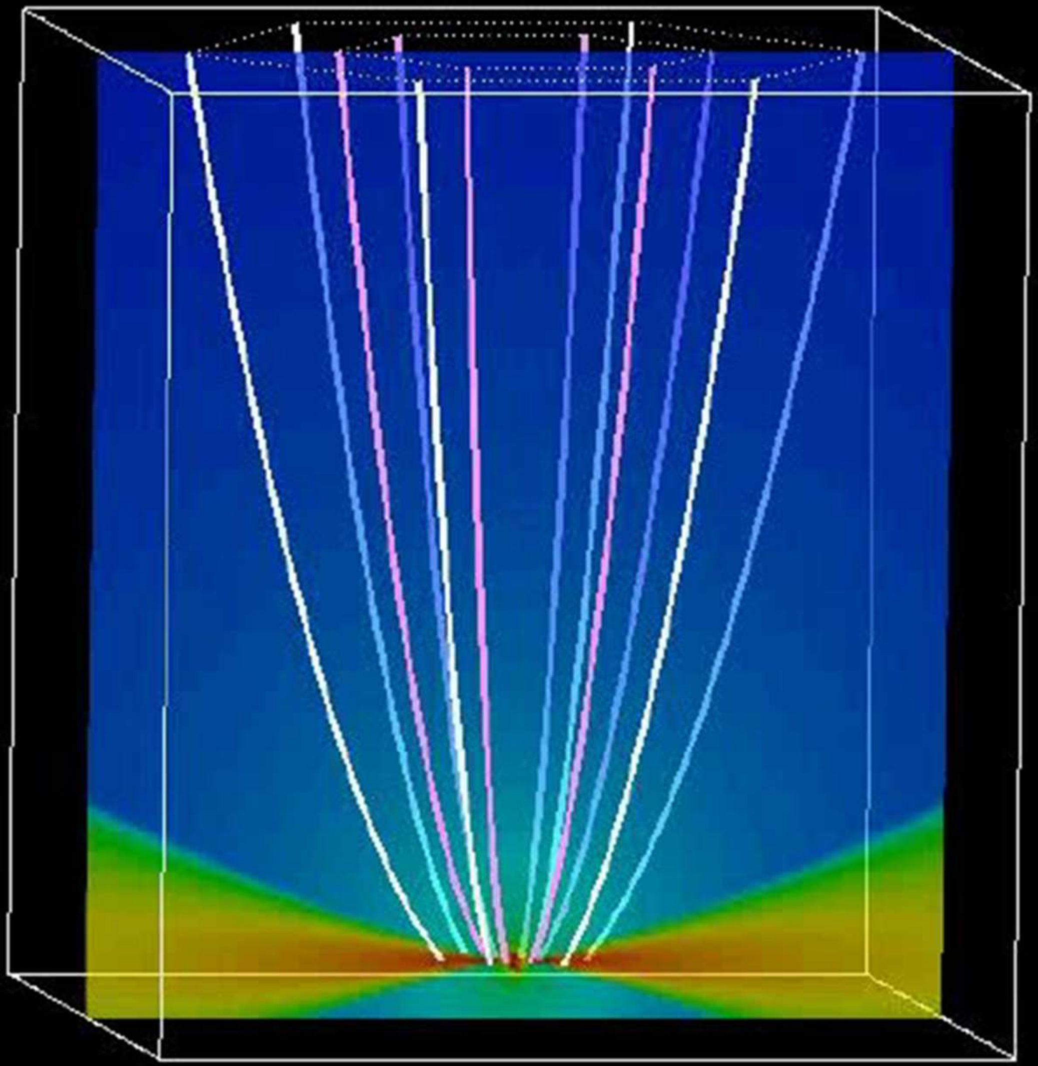
Zeeman-Doppler-Imaging study of II Pegasi - PEPSI/K. G. Strassmeier et al.



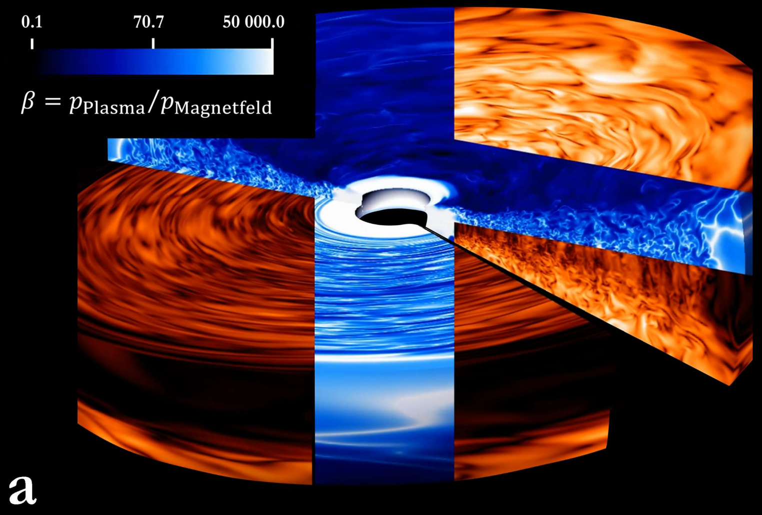
Stellar environment II Pegasi with a magnetic-field extrapolation out to 2.2 stellar radii

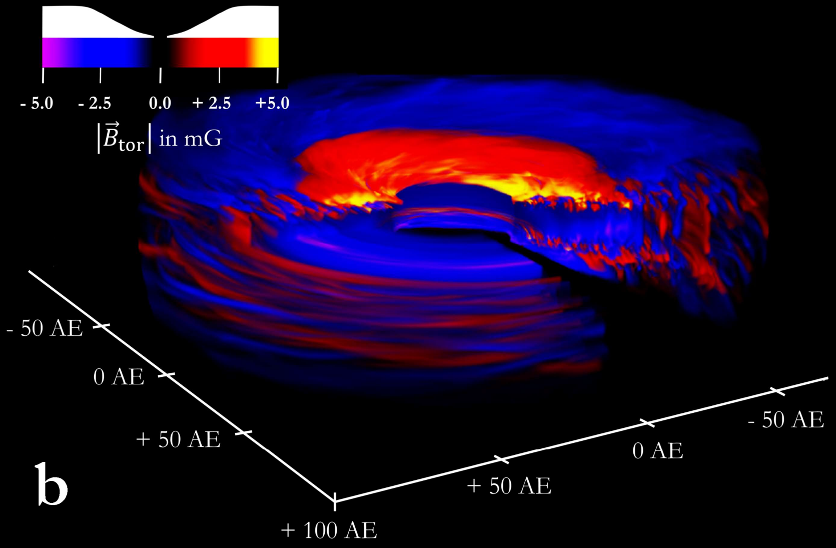


Inflow of matter from the accretion disk via the magnetosphere to the protostar - C. Fendt MPIA Heidelberg



Toroidal winding of magnetic fields in `Tower Jets` - Gakai

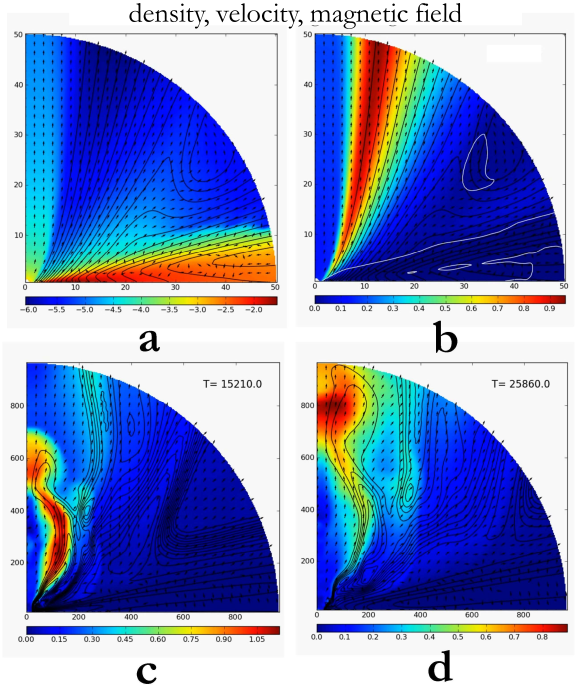

0.1
70.7
50 000.0
$\beta = p_{\mathrm{Plasma}}/p_{\mathrm{Magnetfeld}}$
a

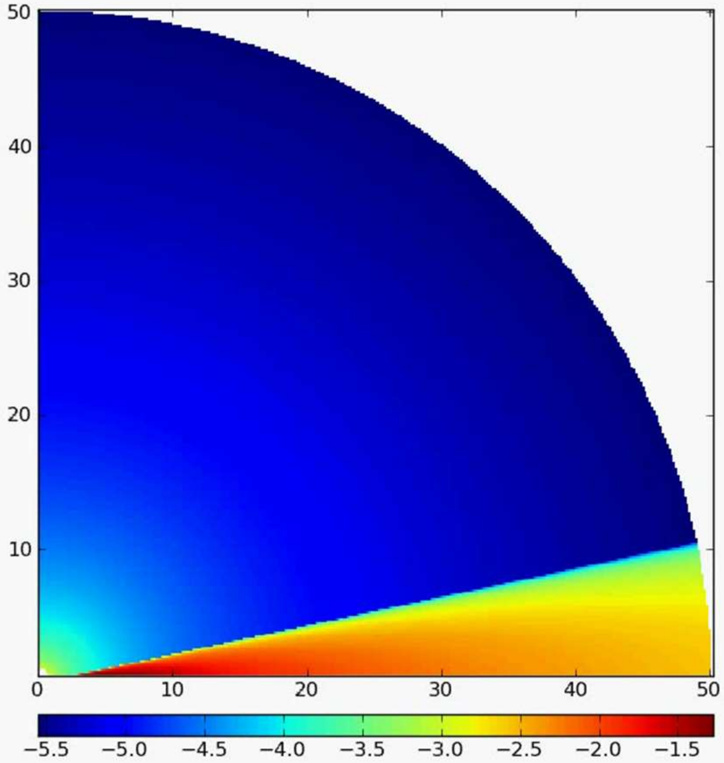

- 5.0
- 2.5
0.0
+ 2.5
+5.0
$|\vec{B}_{\mathrm{tor}}|$ in mG
- 50 AE
0 AE
+ 50 AE
+ 100 AE
+ 50 AE
0 AE
- 50 AE
b

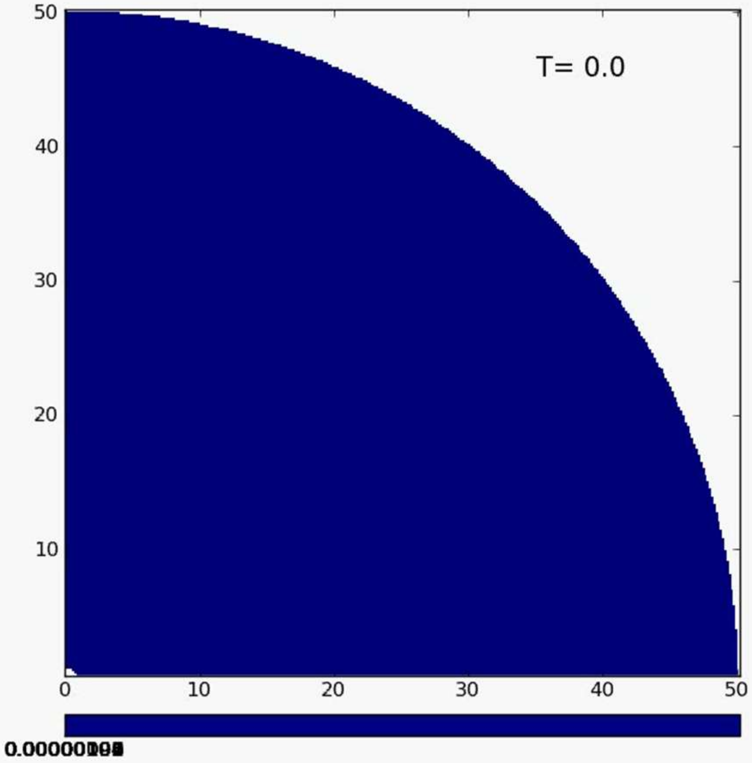
Turbulence and Accretion in 3D Global MHD Simulations of Stratified Protoplanetary Disk

Accretion, disk-jet simulation

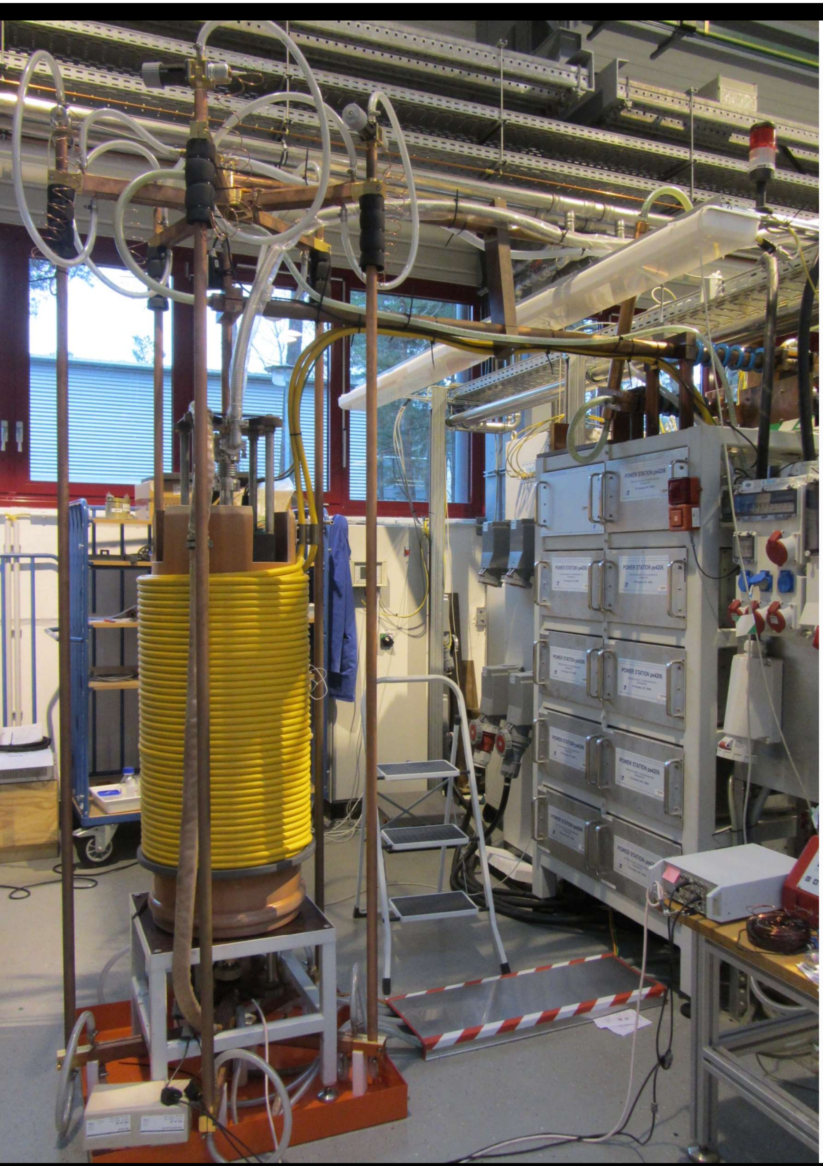
density, velocity, magnetic field



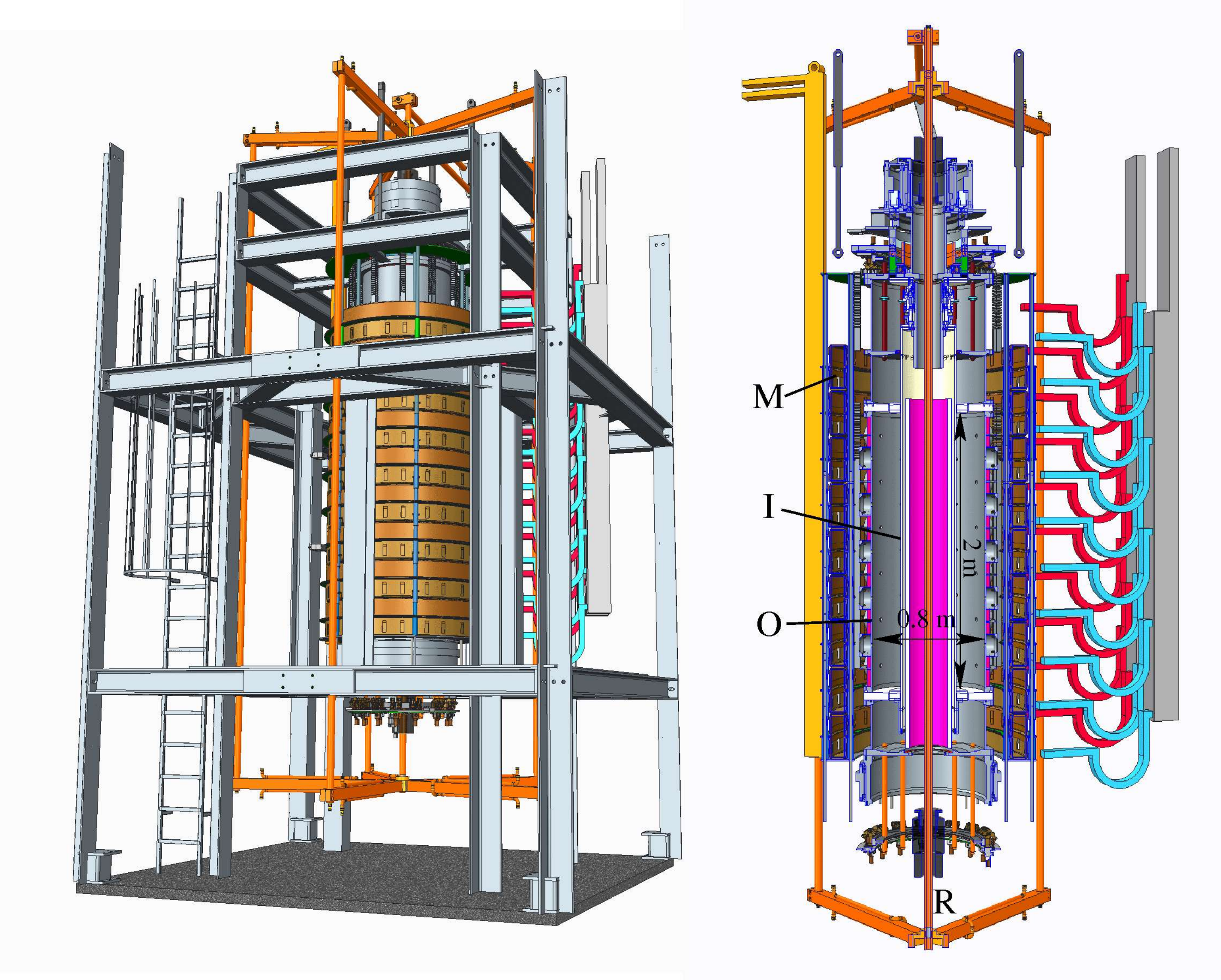




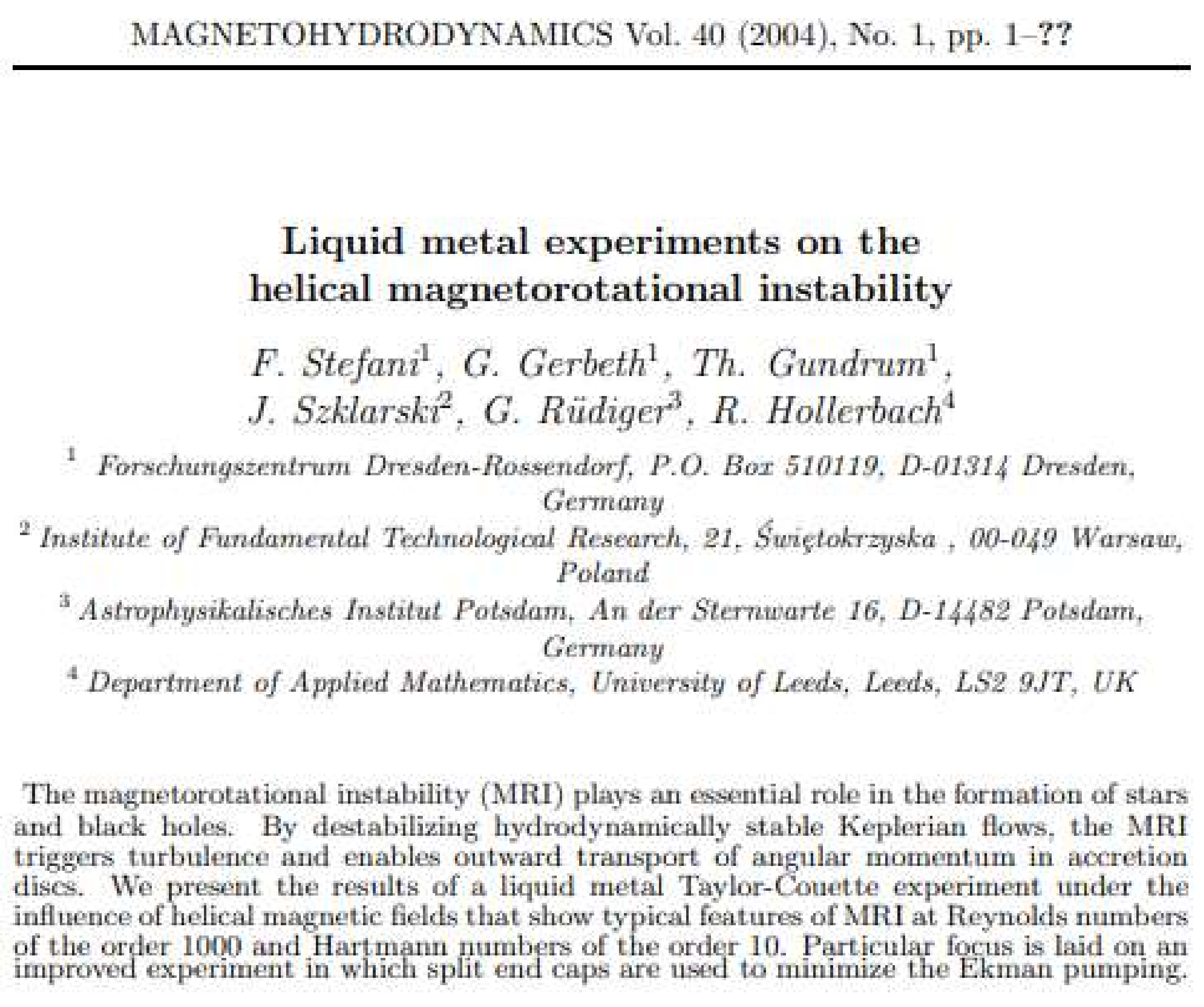
Results of MHD simulations of accretion ejection including magnetic field generation by a disk dynamo - C. Fendt et al.



Setup of the PROMISE Experiment - F. Stefani et al. (FZDR)



Design of the future MRI/TI experiment - F. Stefani et al. (FZDR)



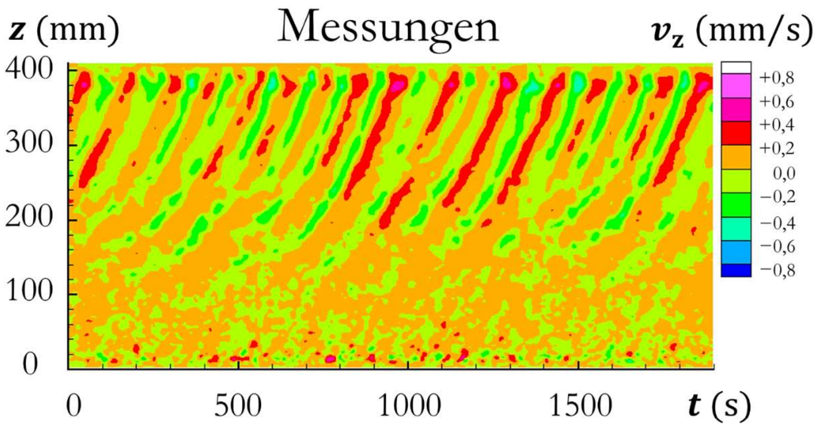
MAGNETOHYDRODYNAMICS Vol. 40 (2004), No. 1, pp. 1–??

Liquid metal experiments on the helical magnetorotational instability

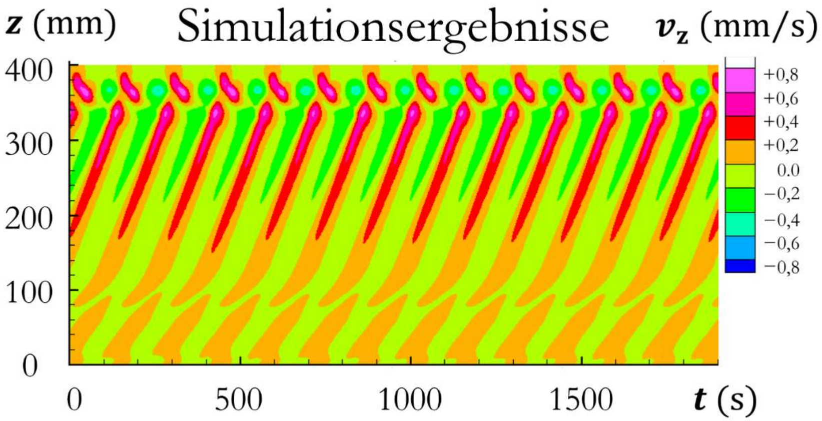
F. Stefani[1], *G. Gerbeth*[1], *Th. Gundrum*[1],
J. Szklarski[2], *G. Rüdiger*[3], *R. Hollerbach*[4]

[1] *Forschungszentrum Dresden-Rossendorf, P.O. Box 510119, D-01314 Dresden, Germany*
[2] *Institute of Fundamental Technological Research, 21, Świętokrzyska , 00-049 Warsaw, Poland*
[3] *Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany*
[4] *Department of Applied Mathematics, University of Leeds, Leeds, LS2 9JT, UK*

The magnetorotational instability (MRI) plays an essential role in the formation of stars and black holes. By destabilizing hydrodynamically stable Keplerian flows, the MRI triggers turbulence and enables outward transport of angular momentum in accretion discs. We present the results of a liquid metal Taylor-Couette experiment under the influence of helical magnetic fields that show typical features of MRI at Reynolds numbers of the order 1000 and Hartmann numbers of the order 10. Particular focus is laid on an improved experiment in which split end caps are used to minimize the Ekman pumping.

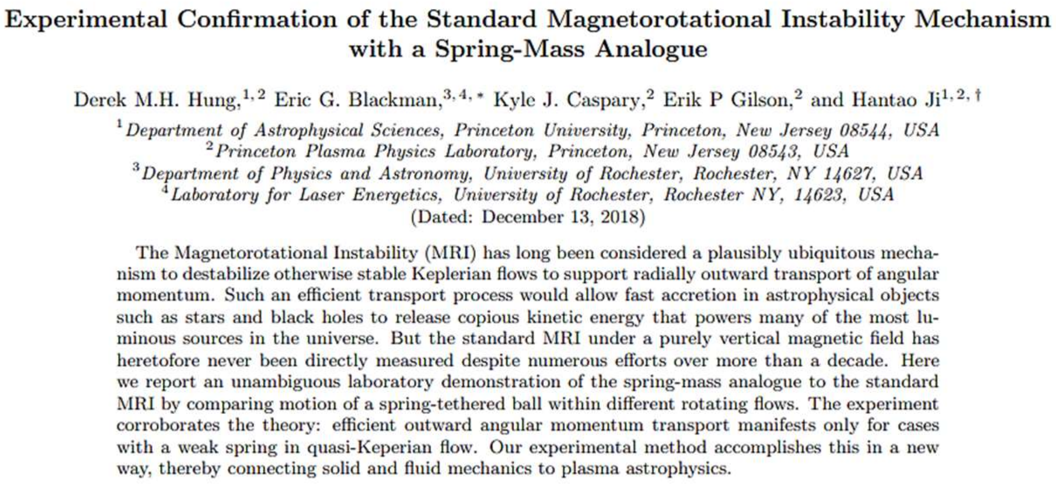


b



c

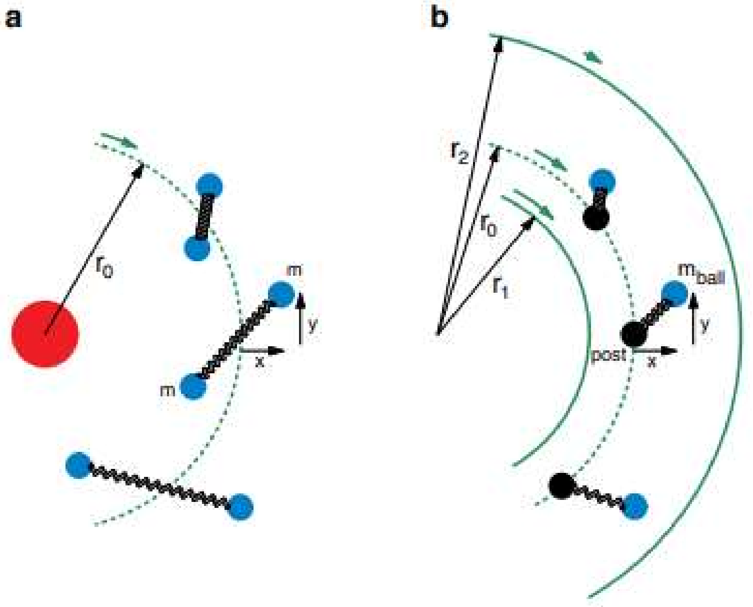
Nachweis der Wirksamkeit der Magnetorotations-Instabilität (MRI) für den Akkretionsprozess mit Hilfe des Potsdam-ROssendorf Magnetic InStability Experiments - G. Rüdiger et al.



Experimental Confirmation of the Standard Magnetorotational Instability Mechanism with a Spring-Mass Analogue

Derek M.H. Hung,[1,2] Eric G. Blackman,[3,4,*] Kyle J. Caspary,[2] Erik P Gilson,[2] and Hantao Ji[1,2,†]
[1]*Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey 08544, USA*
[2]*Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA*
[3]*Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA*
[4]*Laboratory for Laser Energetics, University of Rochester, Rochester NY, 14623, USA*
(Dated: December 13, 2018)

The Magnetorotational Instability (MRI) has long been considered a plausibly ubiquitous mechanism to destabilize otherwise stable Keplerian flows to support radially outward transport of angular momentum. Such an efficient transport process would allow fast accretion in astrophysical objects such as stars and black holes to release copious kinetic energy that powers many of the most luminous sources in the universe. But the standard MRI under a purely vertical magnetic field has heretofore never been directly measured despite numerous efforts over more than a decade. Here we report an unambiguous laboratory demonstration of the spring-mass analogue to the standard MRI by comparing motion of a spring-tethered ball within different rotating flows. The experiment corroborates the theory: efficient outward angular momentum transport manifests only for cases with a weak spring in quasi-Keperian flow. Our experimental method accomplishes this in a new way, thereby connecting solid and fluid mechanics to plasma astrophysics.



Analogues of standard MRI in a purely vertical magnetic field

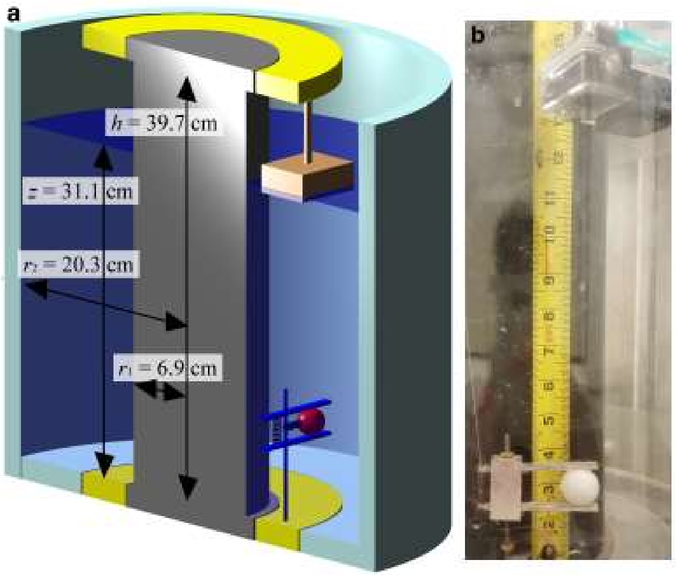
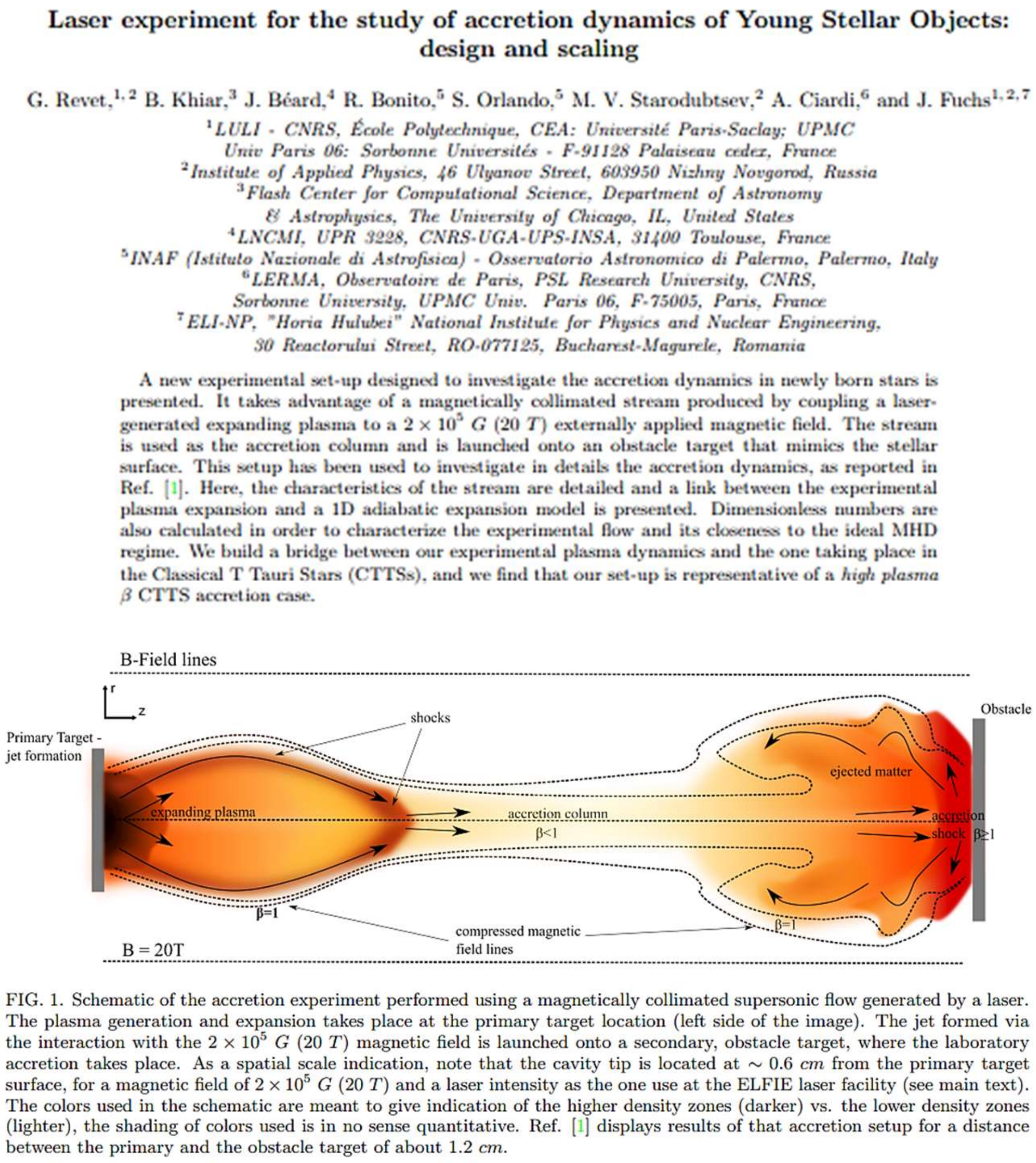


FIG. 4. Experimental apparatus and diagnostics. **a** Schematic of the modified Taylor-Couette device [48], with the inner and outer cylinder radii of $r_1 = 6.9$ cm and $r_2 = 20.3$ cm respectively, and the height of $h = 39.7$ cm. The device was filled with water to a depth of 31.1 cm and the top was open to allow access. A GoPro HERO4 camera was partially submerged to minimize optical distortion. The camera was supported by an attachment and co-rotated with the ring (yellow) at Ω_3. A 1-inch-diameter neutrally buoyant test mass (red) was tethered by an unstretched spring to a vertical post and held by a spring-loaded jaw-clamp. At $t = 0$ a release line (not shown) was pulled from above allowing the vertical spring to relax, releasing the mass. **b** Photograph of the test mass and release mechanism. The camera is visible at the top of the image.

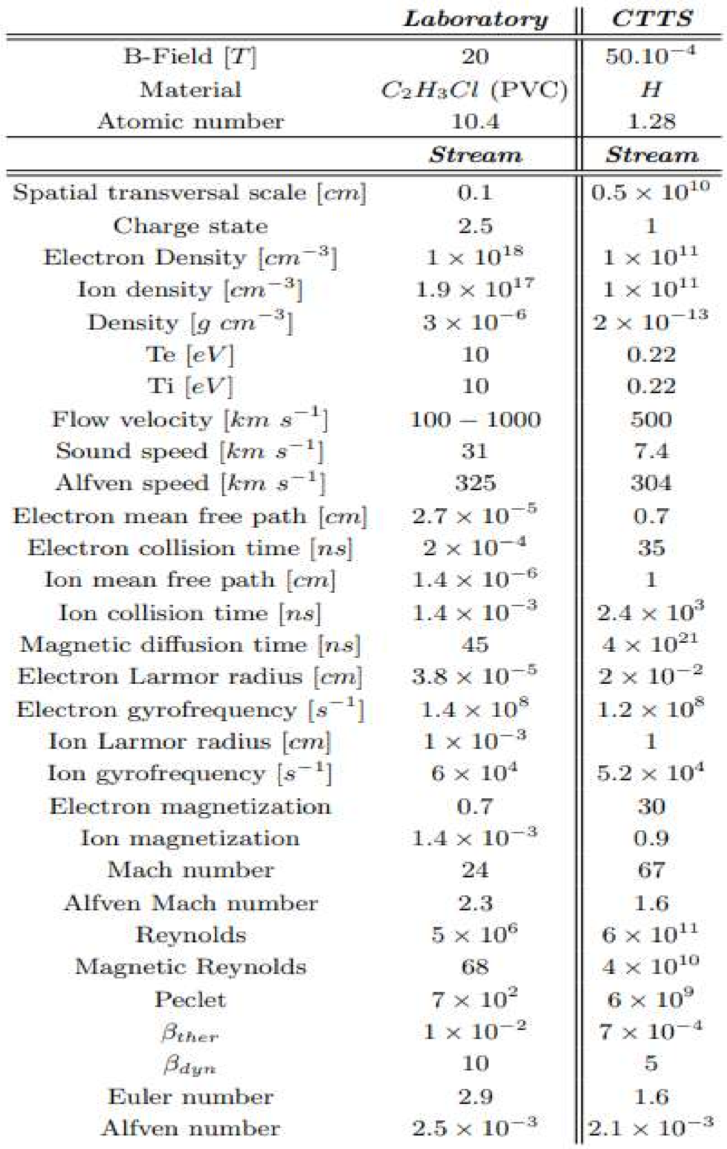


Laser experiment for the study of accretion dynamics of Young Stellar Objects: design and scaling

G. Revet,[1,2] B. Khiar,[3] J. Béard,[4] R. Bonito,[5] S. Orlando,[5] M. V. Starodubtsev,[2] A. Ciardi,[6] and J. Fuchs[1,2,7]
[1]*LULI - CNRS, École Polytechnique, CEA: Université Paris-Saclay; UPMC*
Univ Paris 06: Sorbonne Universités - F-91128 Palaiseau cedex, France
[2]*Institute of Applied Physics, 46 Ulyanov Street, 603950 Nizhny Novgorod, Russia*
[3]*Flash Center for Computational Science, Department of Astronomy*
& Astrophysics, The University of Chicago, IL, United States
[4]*LNCMI, UPR 3228, CNRS-UGA-UPS-INSA, 31400 Toulouse, France*
[5]*INAF (Istituto Nazionale di Astrofisica) - Osservatorio Astronomico di Palermo, Palermo, Italy*
[6]*LERMA, Observatoire de Paris, PSL Research University, CNRS,*
Sorbonne University, UPMC Univ. Paris 06, F-75005, Paris, France
[7]*ELI-NP, "Horia Hulubei" National Institute for Physics and Nuclear Engineering,*
30 Reactorului Street, RO-077125, Bucharest-Magurele, Romania

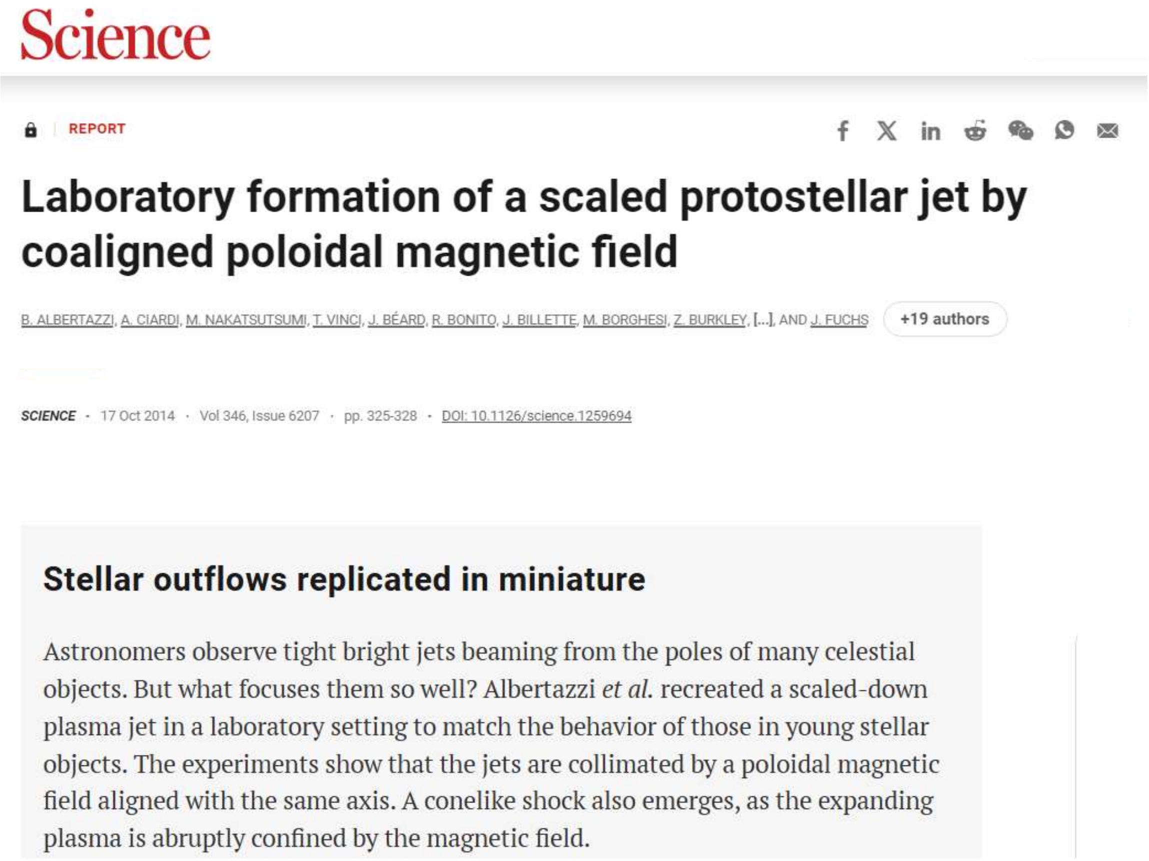
A new experimental set-up designed to investigate the accretion dynamics in newly born stars is presented. It takes advantage of a magnetically collimated stream produced by coupling a laser-generated expanding plasma to a 2×10^5 G (20 T) externally applied magnetic field. The stream is used as the accretion column and is launched onto an obstacle target that mimics the stellar surface. This setup has been used to investigate in details the accretion dynamics, as reported in Ref. [1]. Here, the characteristics of the stream are detailed and a link between the experimental plasma expansion and a 1D adiabatic expansion model is presented. Dimensionless numbers are also calculated in order to characterize the experimental flow and its closeness to the ideal MHD regime. We build a bridge between our experimental plasma dynamics and the one taking place in the Classical T Tauri Stars (CTTSs), and we find that our set-up is representative of a *high plasma* β CTTS accretion case.

FIG. 1. Schematic of the accretion experiment performed using a magnetically collimated supersonic flow generated by a laser. The plasma generation and expansion takes place at the primary target location (left side of the image). The jet formed via the interaction with the 2×10^5 G (20 T) magnetic field is launched onto a secondary, obstacle target, where the laboratory accretion takes place. As a spatial scale indication, note that the cavity tip is located at ~ 0.6 cm from the primary target surface, for a magnetic field of 2×10^5 G (20 T) and a laser intensity as the one use at the ELFIE laser facility (see main text). The colors used in the schematic are meant to give indication of the higher density zones (darker) vs. the lower density zones (lighter), the shading of colors used is in no sense quantitative. Ref. [1] displays results of that accretion setup for a distance between the primary and the obstacle target of about 1.2 cm.



	Laboratory	***CTTS***
B-Field $[T]$	20	50.10^{-4}
Material	C_2H_3Cl (PVC)	H
Atomic number	10.4	1.28
	Stream	***Stream***
Spatial transversal scale $[cm]$	0.1	0.5×10^{10}
Charge state	2.5	1
Electron Density $[cm^{-3}]$	1×10^{18}	1×10^{11}
Ion density $[cm^{-3}]$	1.9×10^{17}	1×10^{11}
Density $[g\ cm^{-3}]$	3×10^{-6}	2×10^{-13}
Te $[eV]$	10	0.22
Ti $[eV]$	10	0.22
Flow velocity $[km\ s^{-1}]$	$100 - 1000$	500
Sound speed $[km\ s^{-1}]$	31	7.4
Alfven speed $[km\ s^{-1}]$	325	304
Electron mean free path $[cm]$	2.7×10^{-5}	0.7
Electron collision time $[ns]$	2×10^{-4}	35
Ion mean free path $[cm]$	1.4×10^{-6}	1
Ion collision time $[ns]$	1.4×10^{-3}	2.4×10^{3}
Magnetic diffusion time $[ns]$	45	4×10^{21}
Electron Larmor radius $[cm]$	3.8×10^{-5}	2×10^{-2}
Electron gyrofrequency $[s^{-1}]$	1.4×10^{8}	1.2×10^{8}
Ion Larmor radius $[cm]$	1×10^{-3}	1
Ion gyrofrequency $[s^{-1}]$	6×10^{4}	5.2×10^{4}
Electron magnetization	0.7	30
Ion magnetization	1.4×10^{-3}	0.9
Mach number	24	67
Alfven Mach number	2.3	1.6
Reynolds	5×10^{6}	6×10^{11}
Magnetic Reynolds	68	4×10^{10}
Peclet	7×10^{2}	6×10^{9}
β_{ther}	1×10^{-2}	7×10^{-4}
β_{dyn}	10	5
Euler number	2.9	1.6
Alfven number	2.5×10^{-3}	2.1×10^{-3}

Parameters of the laboratory accretion stream, with respect to those of the accretion stream in CTTSs, for the incoming stream



Science

REPORT

Laboratory formation of a scaled protostellar jet by coaligned poloidal magnetic field

B. ALBERTAZZI, A. CIARDI, M. NAKATSUTSUMI, T. VINCI, J. BÉARD, R. BONITO, J. BILLETTE, M. BORGHESI, Z. BURKLEY, [...], AND J. FUCHS +19 authors

SCIENCE · 17 Oct 2014 · Vol 346, Issue 6207 · pp. 325-328 · DOI: 10.1126/science.1259694

Stellar outflows replicated in miniature

Astronomers observe tight bright jets beaming from the poles of many celestial objects. But what focuses them so well? Albertazzi *et al.* recreated a scaled-down plasma jet in a laboratory setting to match the behavior of those in young stellar objects. The experiments show that the jets are collimated by a poloidal magnetic field aligned with the same axis. A conelike shock also emerges, as the expanding plasma is abruptly confined by the magnetic field.

Abstract:

Although narrow bipolar jets of matter have been observed to emerge from a wide variety of astrophysical systems, the question of their formation and morphology, past their launching by magneto-centrifugal forces, is still open. Our scaled laboratory experiments, representative of outflows from young stellar objects (YSOs), reveal that stable collimation of the entire flow into a narrow jet can result from the presence of a large-scale poloidal magnetic field that is consistent with observations. The observed plasma flow focuses and creates an interior cavity, giving rise, close to the source, to a standing conical shock from which the jet emerges. Together with astrophysical full-scale simulations, we conclude that this can also explain recently discovered X-ray emission features observed from low-density regions at the base of protostellar jets, such as the well-studied jet HH 154.

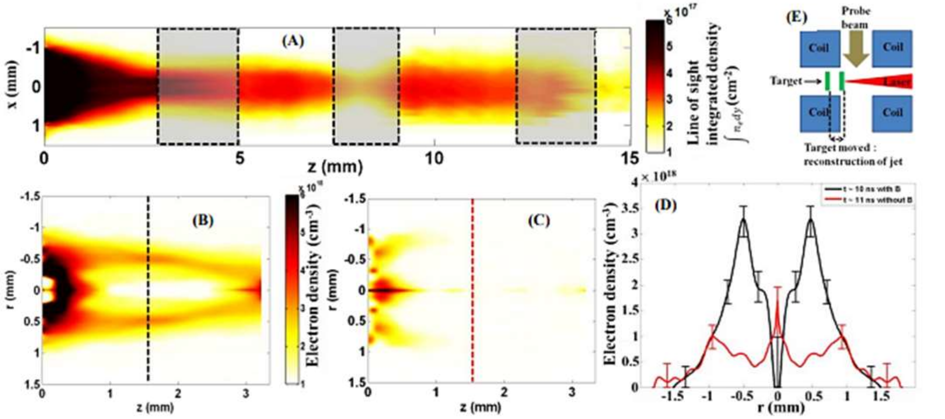
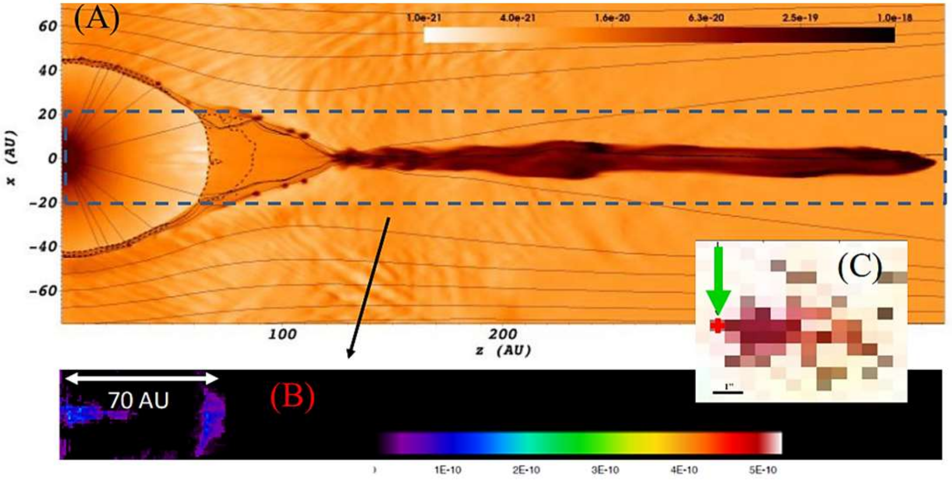
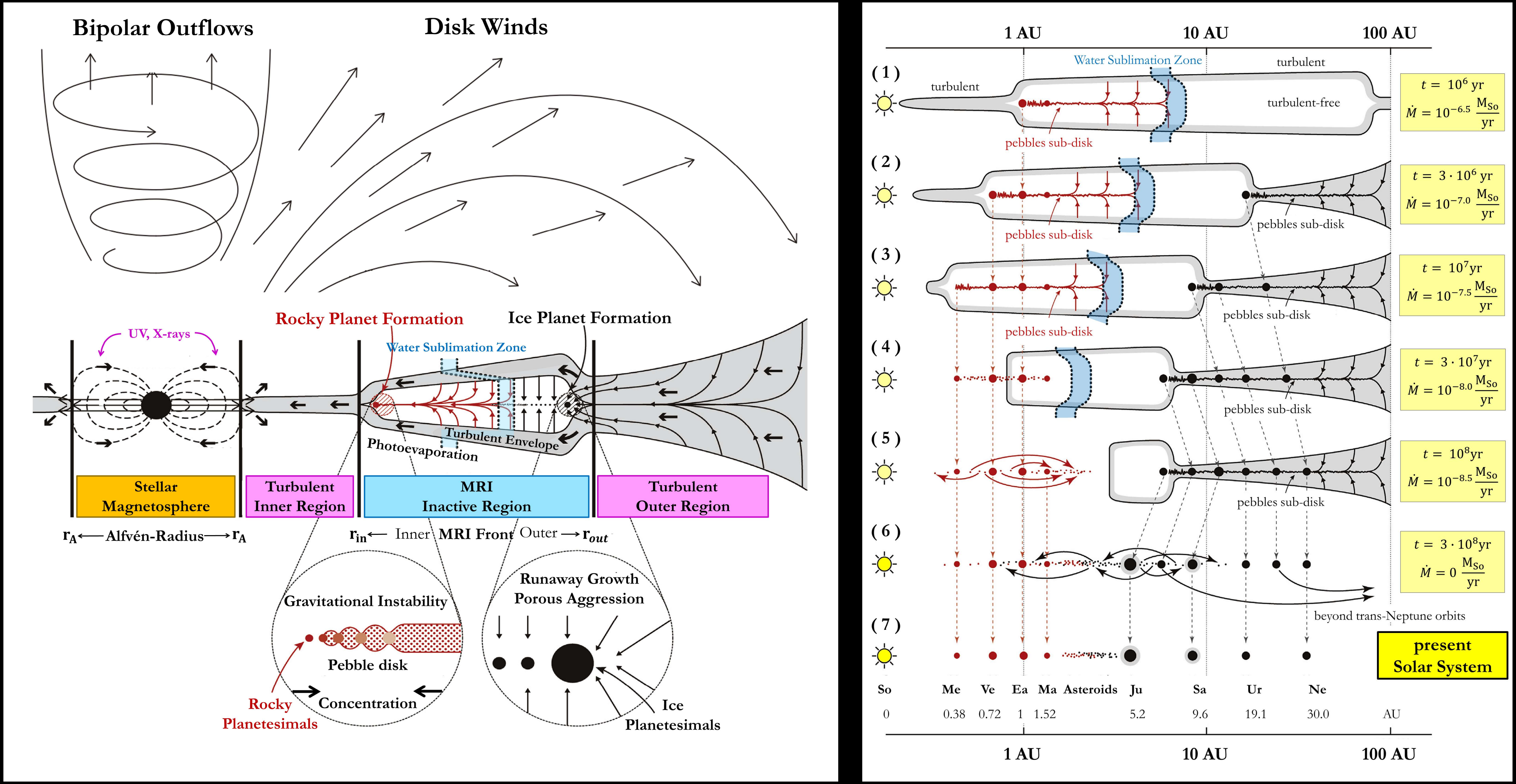


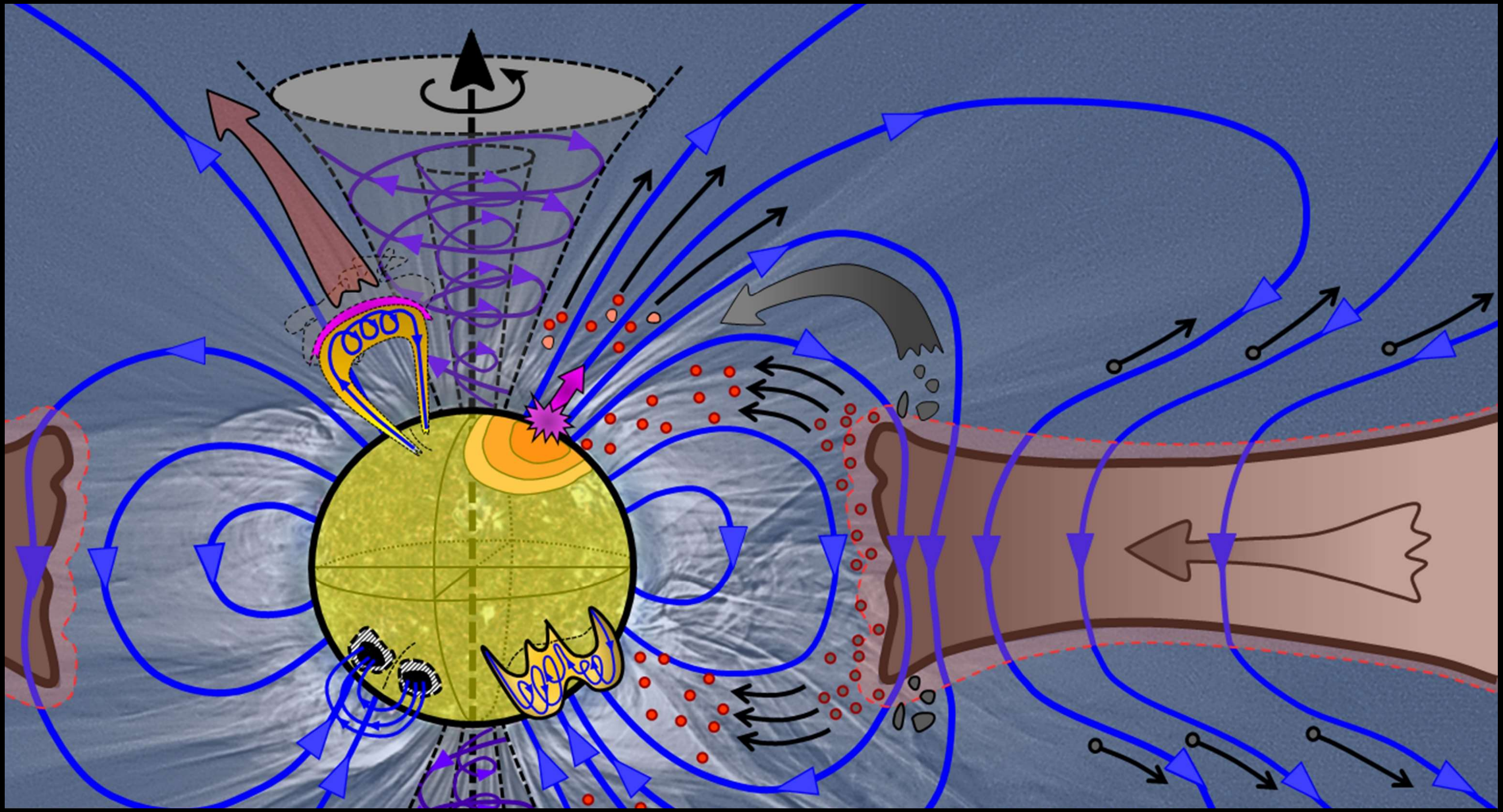
Fig. 1. Laboratory demonstration of jet formation by axial magnetic field. (A) Plasma integrated density measured 20 ns after the laser irradiation (coming from the right) of a CH target (left) immersed in the z-oriented 0.2 MG magnetic field. Four spatially patched images are used (see E). Shaded areas are linear interpolation in between observed sections of the jet. (B-C) Abel inverted density maps in the case with (B) and without (C) magnetic field, and (D) lineouts (along the dashed lines shown in B and C), show the cavity region, and plasma convergence on axis, induced by the magnetic field. The error bars on (D) represent the difference in the plasma density retrieved from the upper and lower measured phase maps (see Methods).



3D simulation of jet formation and collimation in a young star system embedded in a 5 mG axial magnetic field


Bipolar Outflows
Disk Winds
Rocky Planet Formation
Ice Planet Formation
UV, X-rays
Water Sublimation Zone
Turbulent Envelope
Photoevaporation
Stellar Magnetosphere
Turbulent Inner Region
MRI Inactive Region
Turbulent Outer Region
r_A ← Alfvén-Radius → r_A
r_{in} ← Inner MRI Front Outer → r_{out}
Gravitational Instability
Pebble disk
Rocky Planetesimals
Concentration
Runaway Growth
Porous Aggression
Ice Planetesimals
1 AU
10 AU
100 AU
(1)
turbulent
Water Sublimation Zone
turbulent
turbulent-free
pebbles sub-disk
$t = 10^6$ yr
$\dot{M} = 10^{-6.5} \frac{M_{So}}{yr}$
(2)
pebbles sub-disk
pebbles sub-disk
$t = 3 \cdot 10^6$ yr
$\dot{M} = 10^{-7.0} \frac{M_{So}}{yr}$
(3)
pebbles sub-disk
pebbles sub-disk
$t = 10^7$yr
$\dot{M} = 10^{-7.5} \frac{M_{So}}{yr}$
(4)
pebbles sub-disk
$t = 3 \cdot 10^7$yr
$\dot{M} = 10^{-8.0} \frac{M_{So}}{yr}$
(5)
pebbles sub-disk
$t = 10^8$yr
$\dot{M} = 10^{-8.5} \frac{M_{So}}{yr}$
(6)
$t = 3 \cdot 10^8$yr
$\dot{M} = 0 \frac{M_{So}}{yr}$
beyond trans-Neptune orbits
(7)
present Solar System
So
Me
Ve
Ea
Ma
Asteroids
Ju
Sa
Ur
Ne
0
0.38
0.72
1
1.52
5.2
9.6
19.1
30.0
AU
1 AU
10 AU
100 AU

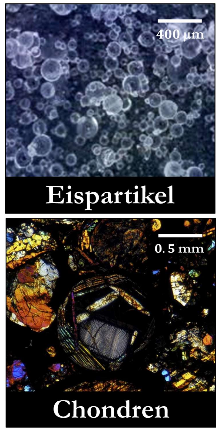
Tandem model of planet formation of solar system-like planetary systems - Y. Imaeda, T. Ebisuzaki

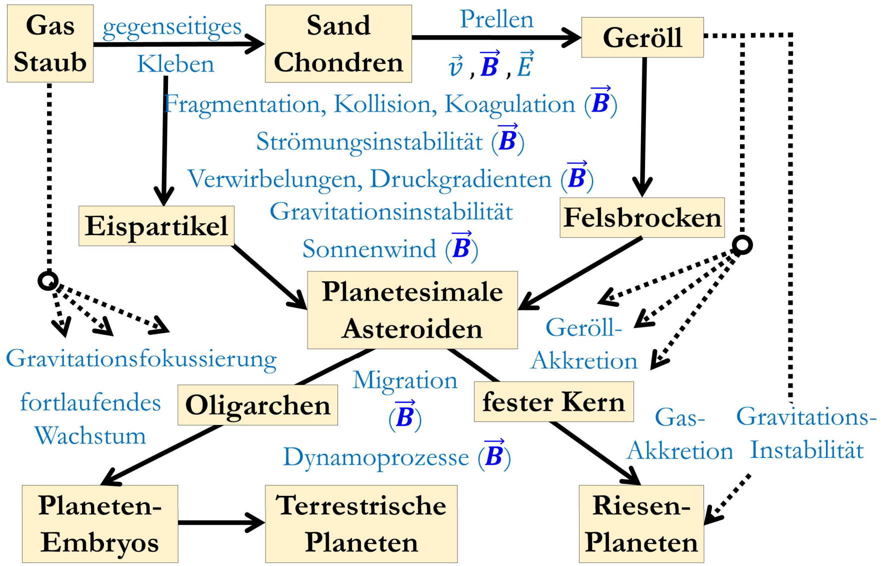


$$\frac{\partial \vec{\boldsymbol{B}}}{\partial \boldsymbol{t}} = \vec{\boldsymbol{\nabla}} \times \left(\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}}\right) - \vec{\boldsymbol{\nabla}} \times \left(\eta_{\mathrm{OD}} \cdot \vec{\boldsymbol{\nabla}} \times \vec{\boldsymbol{B}}\right) + \vec{\boldsymbol{\nabla}} \times \left\{\eta_{\mathrm{AD}} \cdot (\vec{\boldsymbol{\nabla}} \times \vec{\boldsymbol{B}}) \times \vec{\boldsymbol{B}}\right\} - \vec{\boldsymbol{\nabla}} \times \left[\vec{\boldsymbol{\nabla}} \times \left\{\eta_{\mathrm{HD}} \cdot (\vec{\boldsymbol{\nabla}} \times \vec{\boldsymbol{B}}) \times \vec{\boldsymbol{B}}\right\}\right]$$

Exemplarity

10⁻¹⁰m
1 µm
2 cm
3cm
1m
Gas
Staub
Sand
Geröll
Felsbrocken


400 µm
Eispartikel
0.5 mm
Chondren



Gas Staub → gegenseitiges Kleben → **Sand Chondren** → Prellen $\vec{v}, \vec{B}, \vec{E}$ → **Geröll**

Fragmentation, Kollision, Koagulation ($\vec{B}$)

Strömungsinstabilität ($\vec{B}$)

Verwirbelungen, Druckgradienten ($\vec{B}$)

Eispartikel

Gravitationsinstabilität

Felsbrocken

Sonnenwind ($\vec{B}$)

Planetesimale Asteroiden

Gravitationsfokussierung

Geröll-Akkretion

fortlaufendes Wachstum

Oligarchen

Migration ($\vec{B}$)

fester Kern

Gas-Akkretion

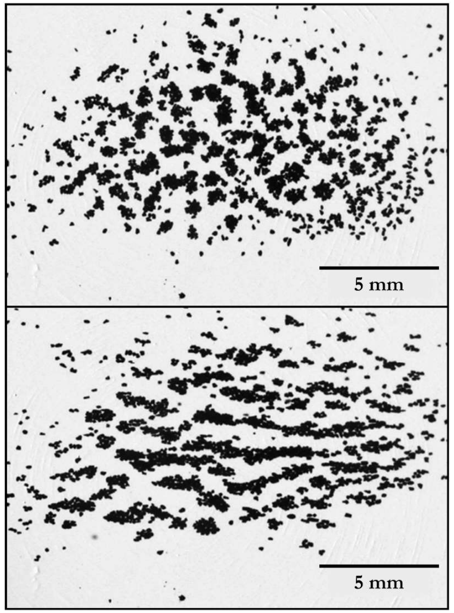
Gravitations-Instabilität

Dynamoprozesse ($\vec{B}$)

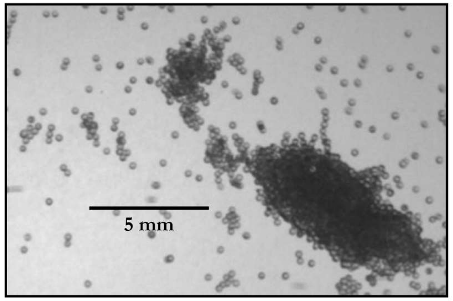
Planeten-Embryos → **Terrestrische Planeten**

Riesen-Planeten

4 km
Planetesimale
3000 km
Felsplaneten
30 000 km
Gasplaneten

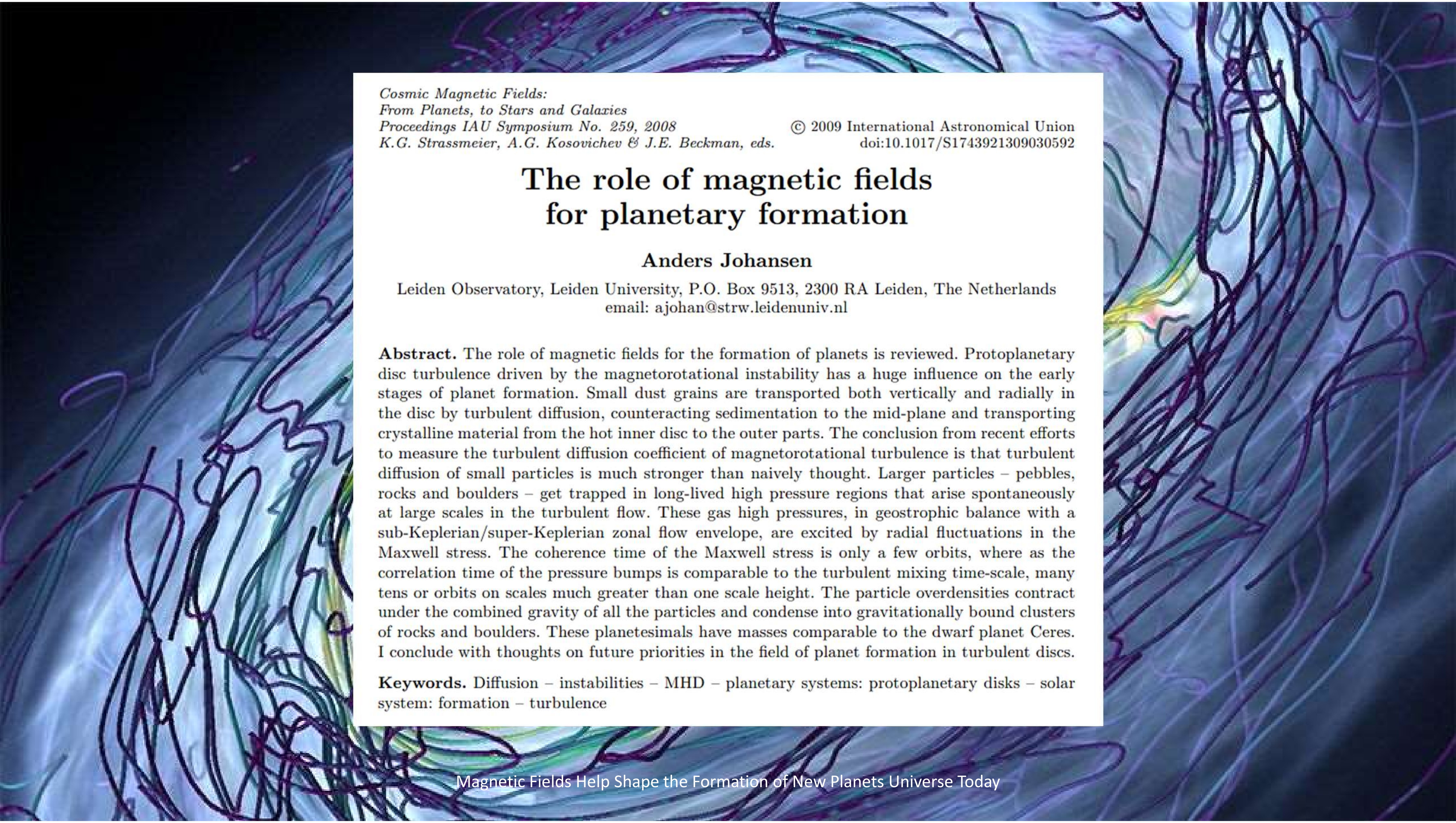


b



c

Formation of planetesimals and planets from dust and gas with possible influences of magnetic fields
U. v. Kusserow, A. S. Stodolna et al., E. K. Jessberger et al., J. Kashuba, NASA/JHUAPL/Southwest Research Institute/R. Tkachenko



Cosmic Magnetic Fields:
From Planets, to Stars and Galaxies
Proceedings IAU Symposium No. 259, 2008
K.G. Strassmeier, A.G. Kosovichev & J.E. Beckman, eds.

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The role of magnetic fields for planetary formation

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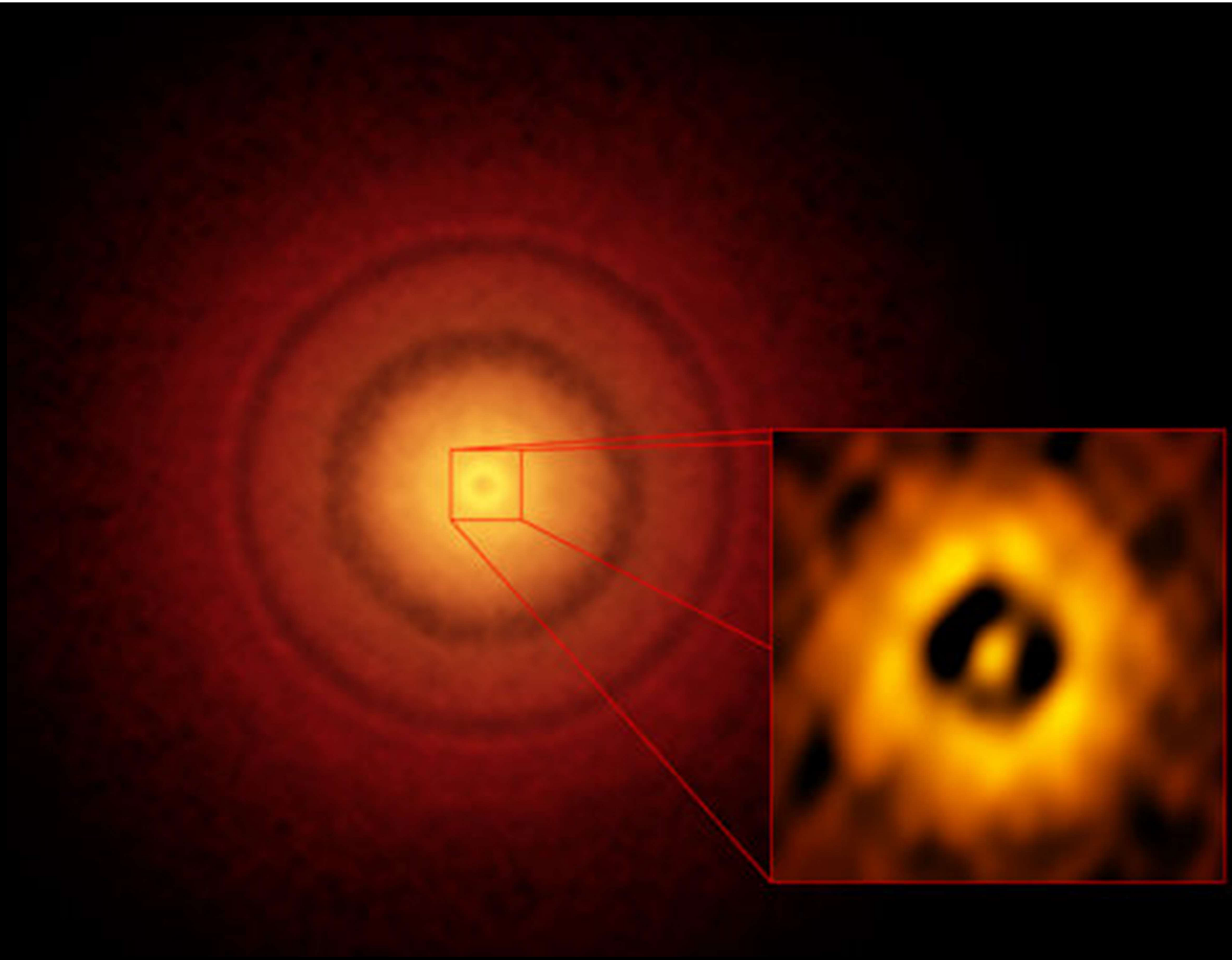
Abstract. The role of magnetic fields for the formation of planets is reviewed. Protoplanetary disc turbulence driven by the magnetorotational instability has a huge influence on the early stages of planet formation. Small dust grains are transported both vertically and radially in the disc by turbulent diffusion, counteracting sedimentation to the mid-plane and transporting crystalline material from the hot inner disc to the outer parts. The conclusion from recent efforts to measure the turbulent diffusion coefficient of magnetorotational turbulence is that turbulent diffusion of small particles is much stronger than naively thought. Larger particles – pebbles, rocks and boulders – get trapped in long-lived high pressure regions that arise spontaneously at large scales in the turbulent flow. These gas high pressures, in geostrophic balance with a sub-Keplerian/super-Keplerian zonal flow envelope, are excited by radial fluctuations in the Maxwell stress. The coherence time of the Maxwell stress is only a few orbits, where as the correlation time of the pressure bumps is comparable to the turbulent mixing time-scale, many tens or orbits on scales much greater than one scale height. The particle overdensities contract under the combined gravity of all the particles and condense into gravitationally bound clusters of rocks and boulders. These planetesimals have masses comparable to the dwarf planet Ceres. I conclude with thoughts on future priorities in the field of planet formation in turbulent discs.

Keywords. Diffusion – instabilities – MHD – planetary systems: protoplanetary disks – solar system: formation – turbulence

Magnetic Fields Help Shape the Formation of New Planets Universe Today



Sun-like Star TW Hydrae - S. Andrews (Harvard-Smithsonian CfA), ALMA (ESO/NAOJ/NRAO) |

Draft version February 6, 2023
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Three-dimensional Global Simulations of Type-II Planet-disk Interaction with a Magnetized Disk Wind: I. Magnetic Flux Concentration and Gap Properties

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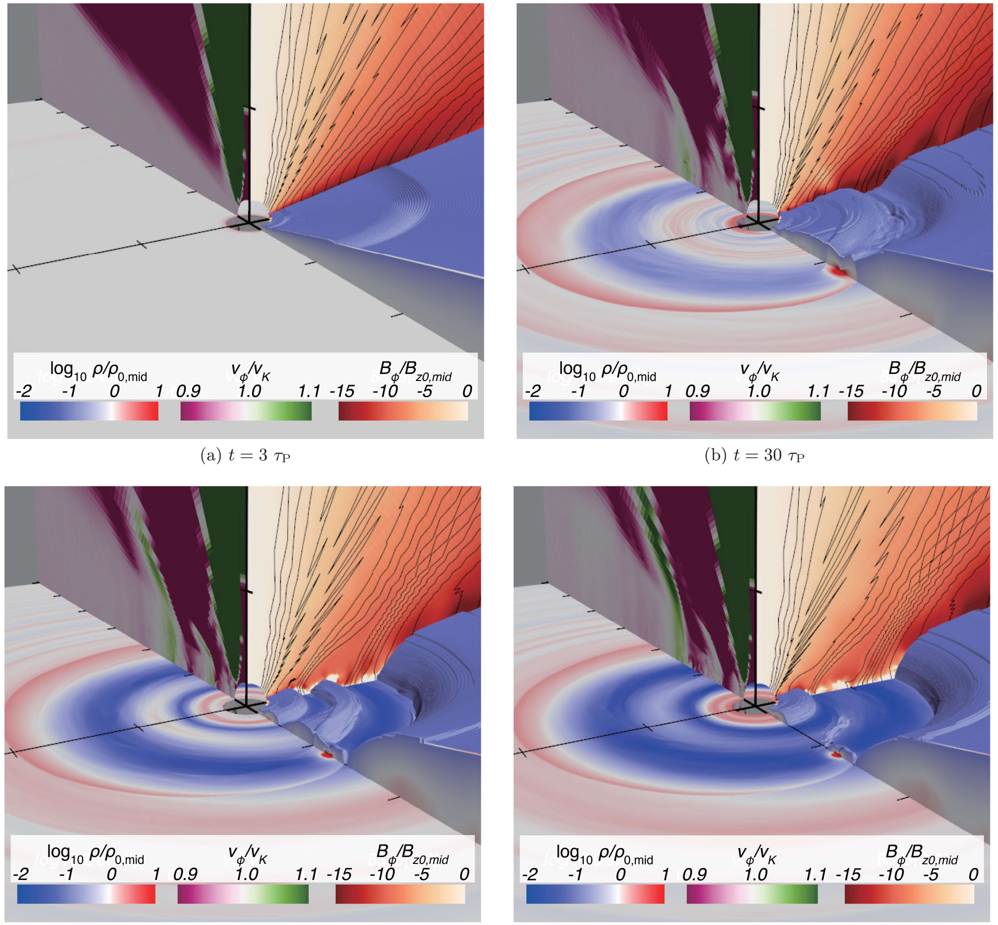
ABSTRACT

Giant planets embedded in protoplanetary disks (PPDs) can create annulus density gaps around their orbits in the type-II regime, potentially responsible for the ubiquity of annular substructures observed in PPDs. Despite of substantial amount of works studying type-II planet migration and gap properties, they are almost exclusively conducted under the viscous accretion disk framework. However, recent studies have established magnetized disk winds as the primary driving disk accretion and evolution, which can co-exist with turbulence from the magneto-rotational instability (MRI) in the outer PPDs. We conduct a series of 3D global non-ideal magneto-hydrodynamic (MHD) simulations of type-II planet-disk interaction applicable to the outer PPDs. Our simulations properly resolve the MRI turbulence and accommodate the MHD disk wind. We found that the planet triggers the poloidal magnetic flux concentration around its orbit. The concentrated magnetic flux strongly enhances angular momentum removal in the gap, which is along the inclined poloidal field through a strong outflow emanating from the disk surface outward of the planet gap. The resulting planet-induced gap shape is more similar to an inviscid disk, while being much deeper, which can be understood from a simple inhomogeneous wind torque prescription. The corotation region is characterized by a fast trans-sonic accretion flow that is asymmetric in azimuth about the planet and lacking the horseshoe turns, and the meridional flow is weakened. The torque acting on the planet generally drives inward migration, though the migration rate can be affected by the presence of neighboring gaps through stochastic, planet-free magnetic flux concentration.

Keywords: Extrasolar gaseous giant planets, Magnetohydrodynamical simulations, Protoplanetary disks, Planet formation



(a) $t = 3\ \tau_{\rm P}$

(b) $t = 30\ \tau_{\rm P}$

(c) $t = 100\ \tau_{\rm P}$

(d) $t = 140\ \tau_{\rm P}$

Figure 1. Snapshots of simulation results at $t = 3$, 30, 100, and 140 $\tau_{\rm P}$ in the fiducial run Mt1Am3. In each panel, the bottom slice shows the midplane density, the left and right vertical walls show ϕ-averaged v_ϕ/v_K and $B_\phi/B_{z,0}$, respectively, and the blue iso-surface marks a constant density of $\rho = \rho_{0,\rm mid}\ {\rm e}^{-2H}$, where $\rho_{0,\rm mid} = \rho_0 R^{-q_\rho}$. The black lines on the right wall show the contours of equi-spaced azimuthally-averaged poloidal magnetic fluxes. Along the three axes ($x = R\sin\phi$, $y = R\cos\phi$, z), the black ticks have a uniform spacing of 5 in code units.

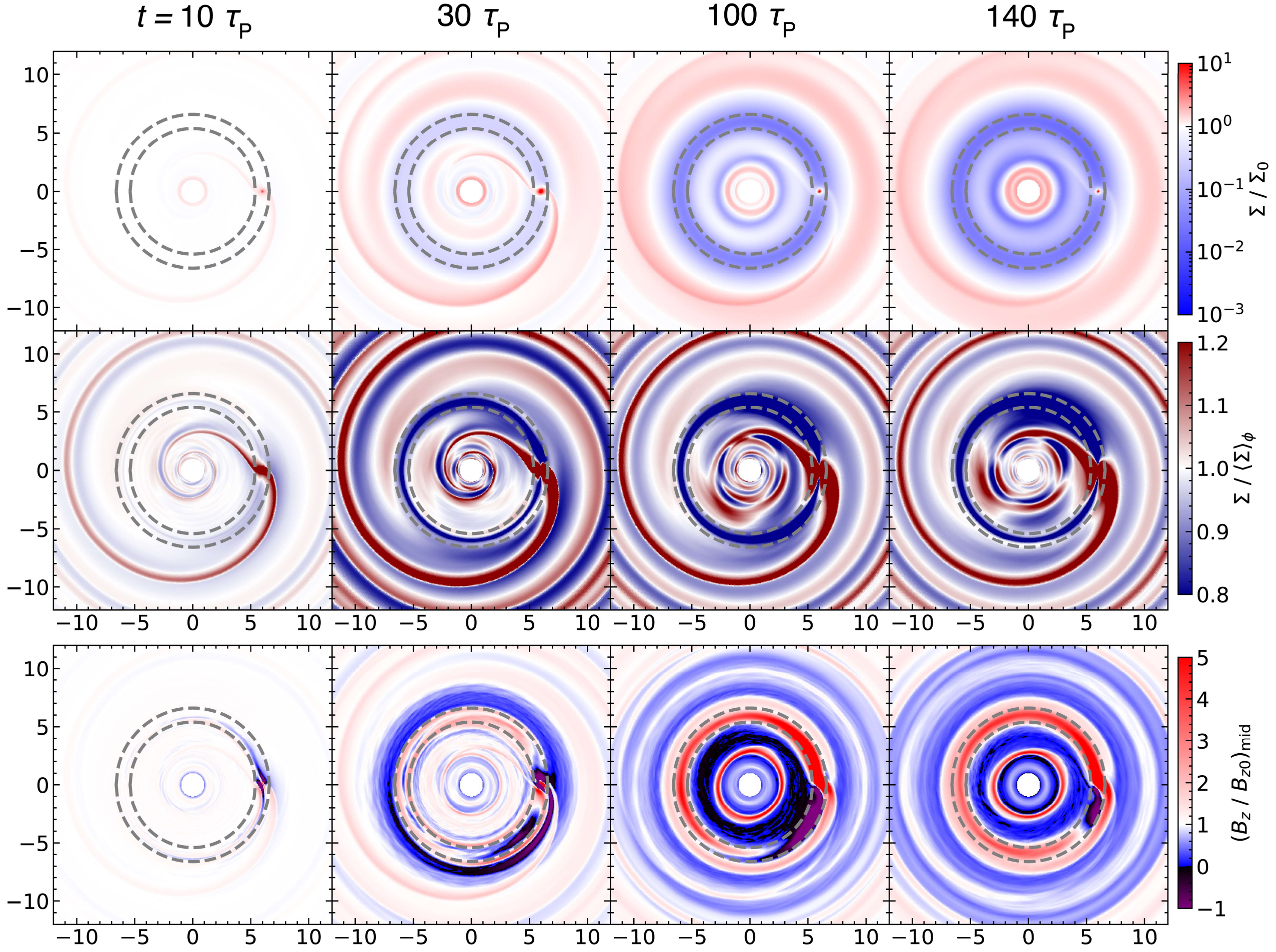


Figure 2. R-ϕ plots of surface density (top) and vertical magnetic field averaged within $|z| < H$ (bottom) normalized by the initial values and surface density normalized by the average at the orbit (middle), at t = 10, 30, 100, and 140 $\tau_{\rm P}$ from left to right. The time average is taken over 10 $\tau_{\rm P}$ before the quoted values. The grey dashed circles correspond to $R = R_{\rm P} \pm r_{\rm H}$.

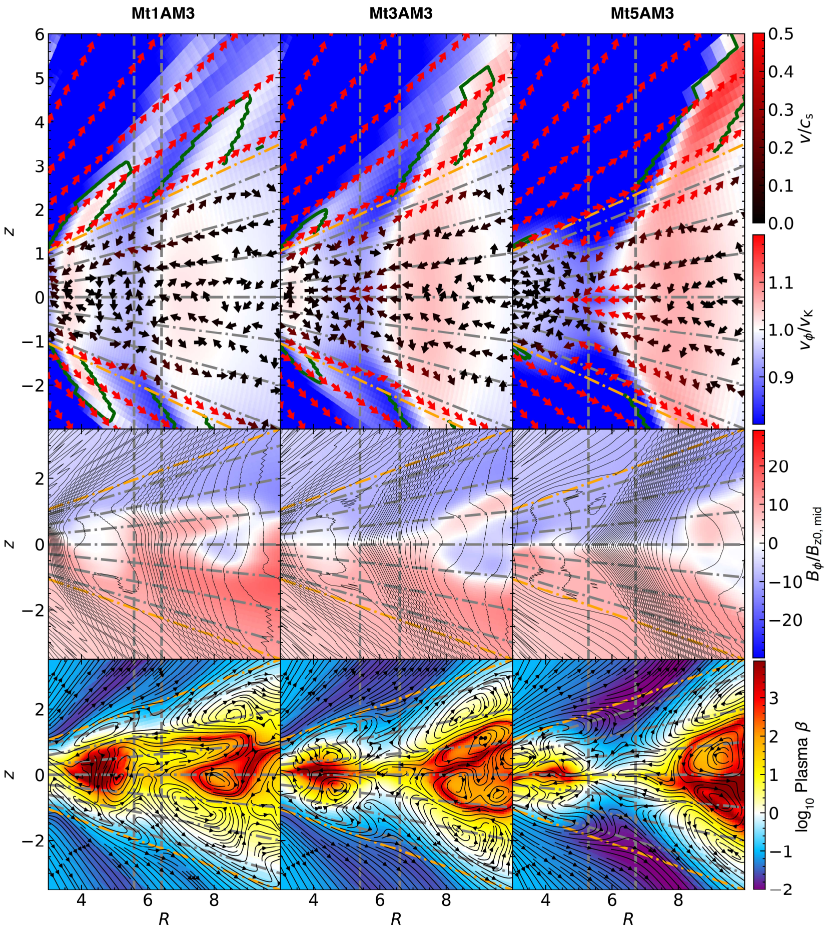
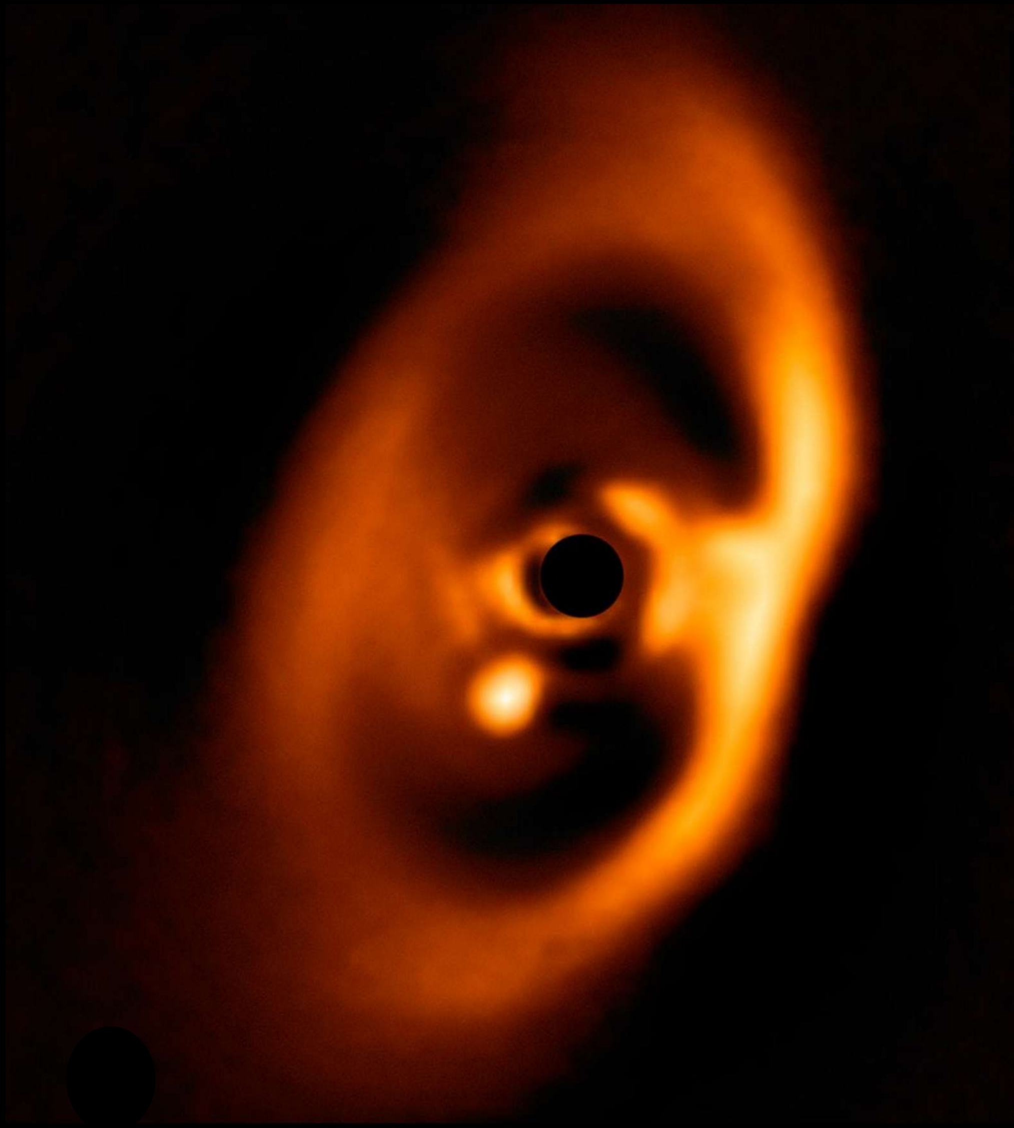
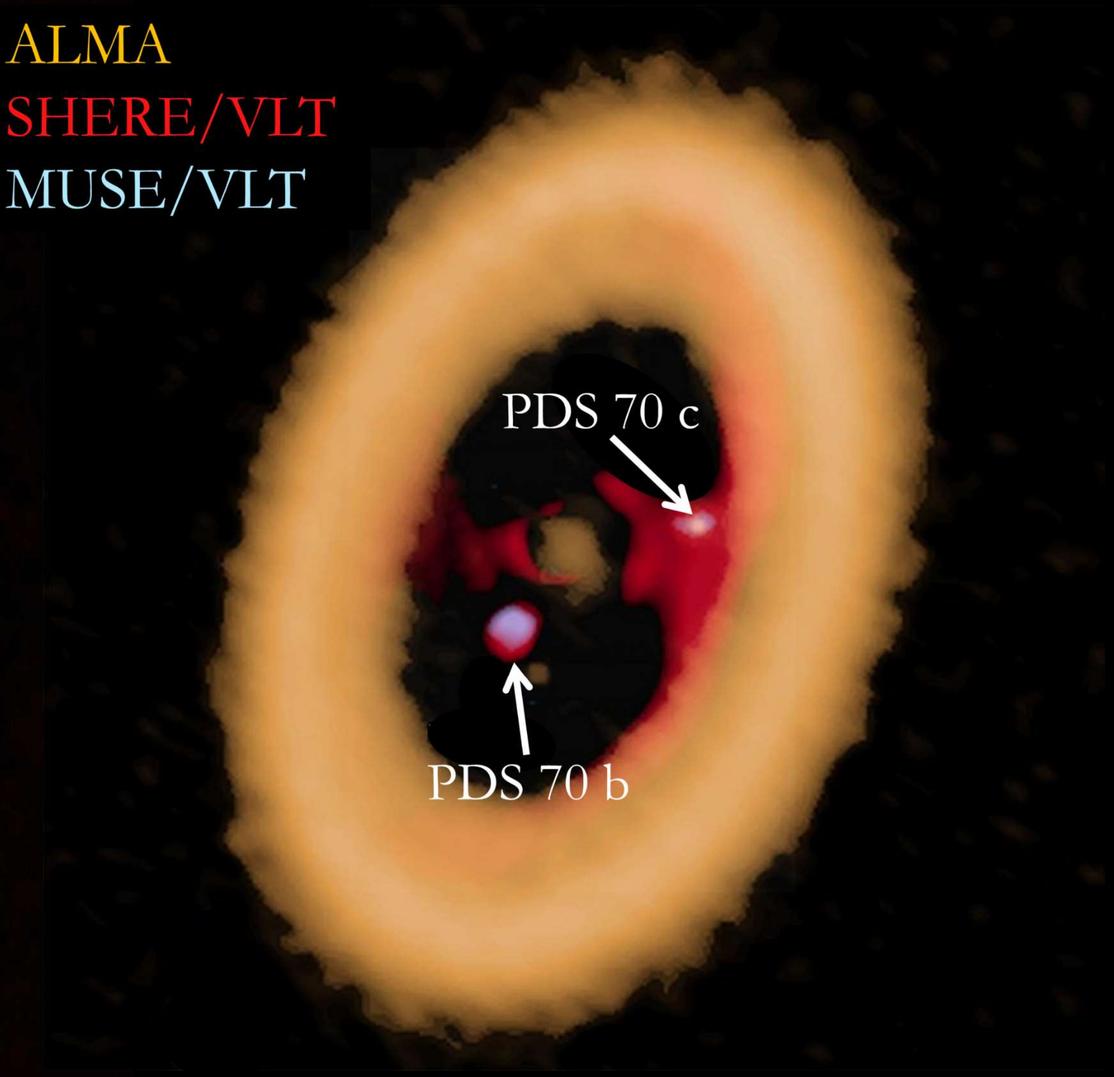


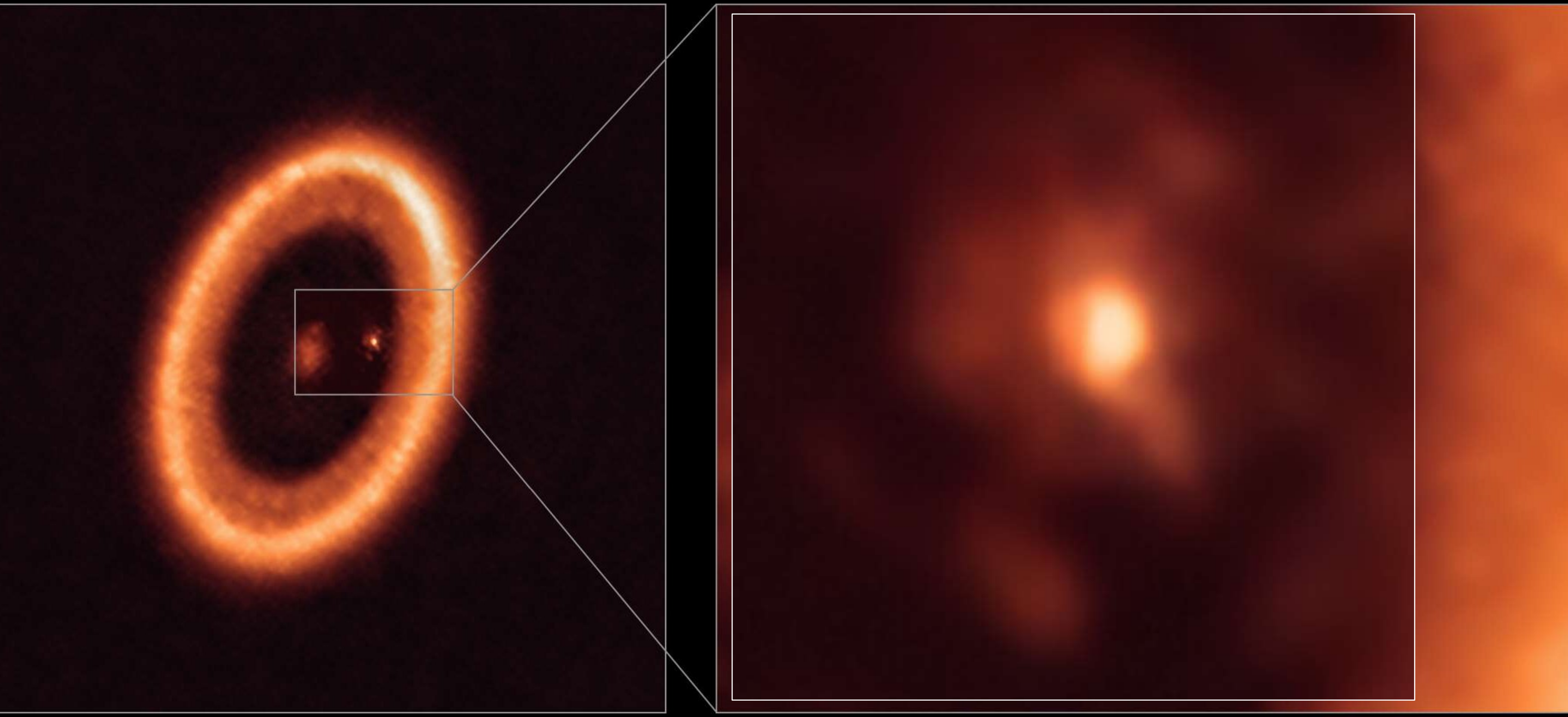
Figure 11. The $R - z$ slices of the disk in Mt1Am3, Mt3Am3, and Mt5Am3 from left to right, respectively. Top: poloidal velocity (arrow) and disk-rotation velocity (background color). Middle: isocontour of the poloidal magnetic flux function $\Phi_{\rm B}$ and toroidal magnetic field (background color). Bottom: momentum streamline (black lines) and plasma β (background color). All quantities are averaged in $0 < \phi < 2\pi$ and $130 < t/\tau_{\rm P} < 140$. The vertical and horizontal grey dashed lines show $R = R_{\rm P} \pm r_{\rm H}$ and z/H =-3, -2, -1, 0, 1, 2, 3 from bottom to top, respectively. The orange dash-dotted and green lines correspond to the disk surface ($z/H = 3.5$) and Alfvén surface where the poloidal velocity equals to the poloidal Alfvén velocity. Note that $v_{\rm K}$ is based on cylindrical coordinates, and $B_{z0,\rm mid}$ is the initial vertical field in the midplane.



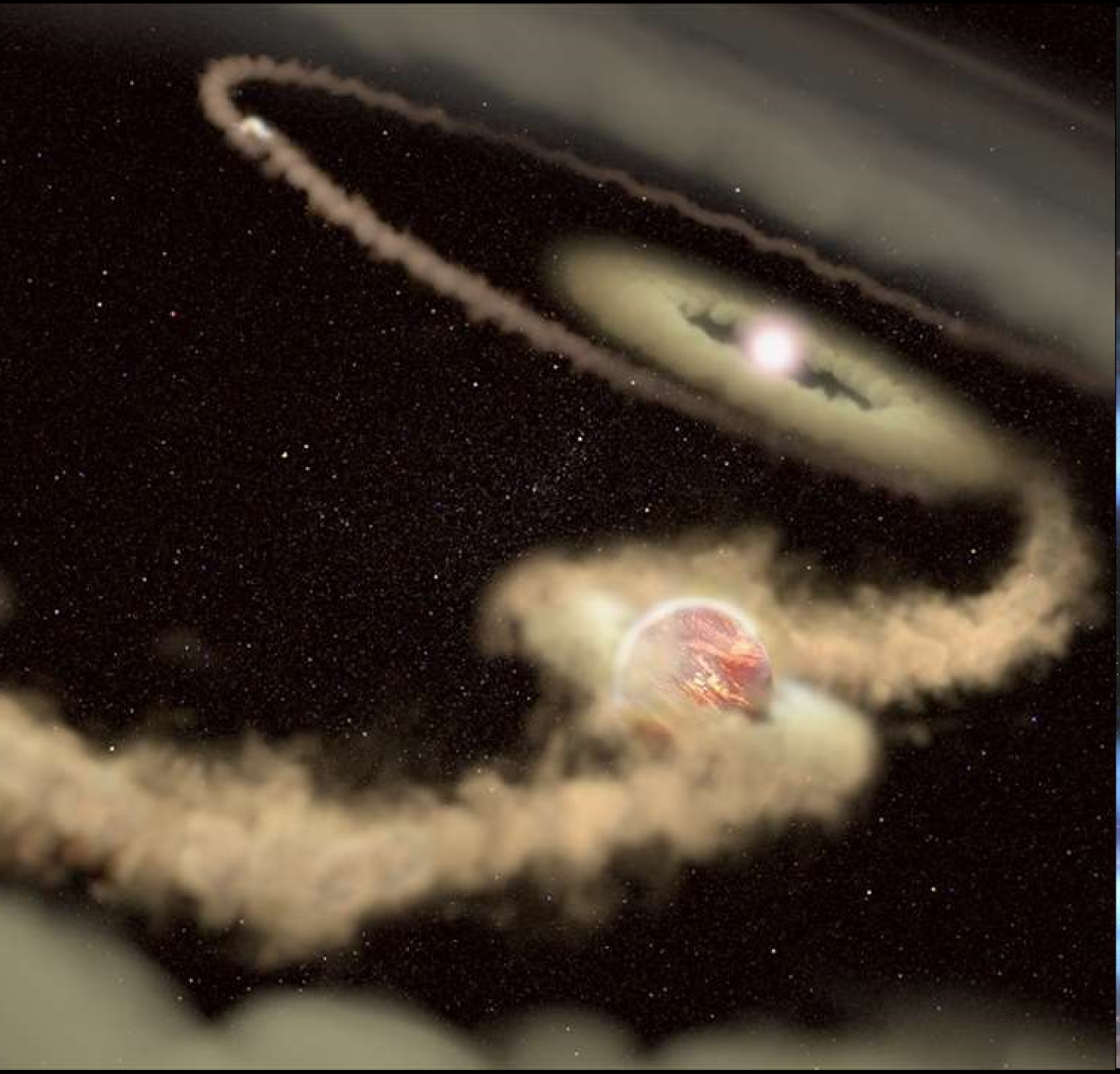
Protoplanetary disk of PDS 70 with the planet PDS 70b - VLT/ SPHERE ESO/A. Müller et al.


ALMA
SHERE/VLT
MUSE/VLT
PDS 70 c
PDS 70 b

ALMA and VLT datas in a composite image of PDS 70 - ALMA (ESO/NOAJ/NRAO) A. Isella; ESO



Close-up view showing PDS 70b and PDS 70c with its “circumplanetary disk” - ALMA (ESO/NAOJ/NRAO)/Benisty et al.



Artist's illustration of exoplanets PDS 70 b and c - J. Olmsted (STScI)

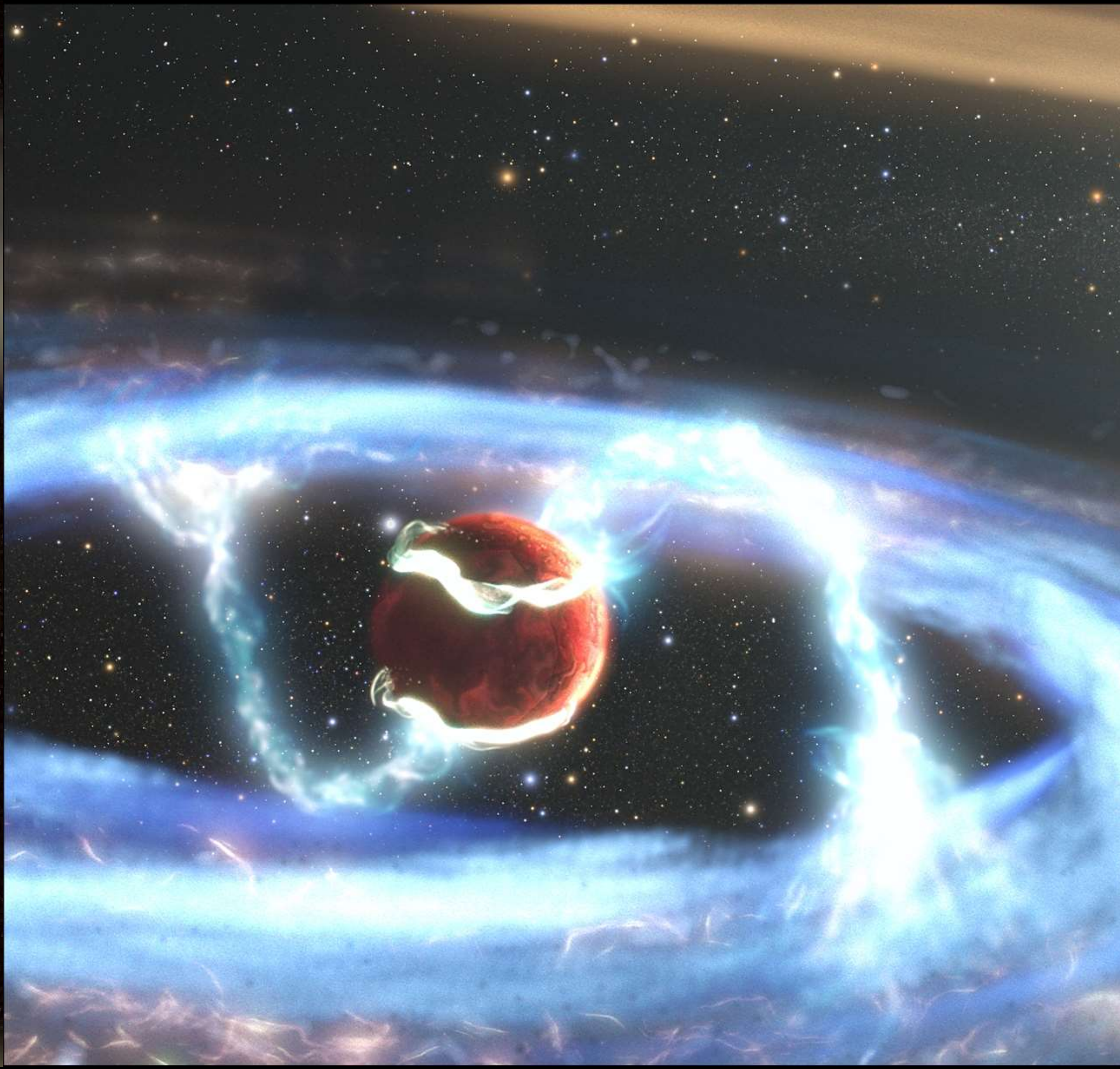


Illustration of the forming exoplanet PDS 70b collecting material from a circumplanetary disk
McDonald Observatory–University of Texas, Y. Zhou (UT Austin)

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Effective dust growth in laminar circumplanetary discs with magnetic wind-driven accretion

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ABSTRACT

It has been considered that large satellites around gas planets form *in situ* circumplanetary discs (CPDs). However, dust particles supplied into CPDs drift toward the central planets before they grow into satellitesimals, building blocks of the satellites. We investigate the dust growth in laminar CPDs with magnetic wind-driven accretion. In such laminar discs, dust particles can settle on to the mid-plane and grow large by mutual collision more efficient than in classical turbulent CPDs. First, we carry out 3D local MHD simulations of a CPD including all the non-ideal MHD effects (Ohmic resistivity, Hall effect, and ambipolar diffusion). We investigate if the disc accretion can be governed by magnetic wind-driven accretion and how laminar the disc can be, in a situation where the magnetic disc wind can be launched from the disc. Secondly, we model 1D steady CPDs consistent with the results of the MHD simulations and calculate the steady radial distributions of the dust profiles in the modelled discs, taking account of the collisional growth, radial drift, fragmentation, and vertical stirring by the Kelvin–Helmholtz instability. We show that satellitesimals can form in such CPDs if the dust-to-gas mass ratio of the inflow to the discs is larger than 0.02, which is 50 times smaller than the critical value in turbulent CPDs. This condition can be satisfied when enough amount of dust piles up at the gas pressure bump created by the planets. This result shows that satellitesimals would form in laminar CPDs with magnetic wind-driven accretion.

Key words: accretion, accretion discs – MHD – planets and satellites: formation.

1 INTRODUCTION

It is generally accepted that the large satellites around Jupiter and Saturn formed from small solid materials inside their circumplanetary discs (CPDs), byproducts of the gas accretion of the gas planets, like planets form in protoplanetary discs (PPDs). There are mainly two *in situ* formation scenarios for the major satellites: the satellitesimal-accretion scenario (e.g. Mosqueira & Estrada 2003; Canup & Ward 2006) and the pebble-accretion scenario (Shibaike et al. 2019; Ronnet & Johansen 2020). The former needs a lot of satellitesimals (km sized or larger), building blocks of the satellites, but the satellitesimal formation is not easy. Dust particles supplied to the disc quickly grow to pebbles (cm–m sized) by their mutual collision, but they then fall into the central planets due to the headwind receiving from the gas rotating with sub-Keplerian speed. Shibaike et al. (2017) found that the *in situ* formation of satellitesimals is difficult unless the dust-to-gas mass ratio of the inflow on to the CPDs is larger than unity, which is not realistic (Homma et al. 2020; Szulágyi, Binkert & Surville 2022). On the other hand, Drażkowska & Szulágyi (2018) and Batygin & Morbidelli (2020) argued that if the discs have strong radial outflows on the mid-planes, the particles can pile up at the points where the inward drift and the outward advection are balanced and satellitesimals form by the streaming instability from the gathered particles. In this work, we propose another solution to avoid the drift barrier to the satellitesimal formation.

Previous works modelled their CPDs as the classical α disc models (Shakura & Sunyaev 1973), where their dynamics and evolution are governed by single parameter α, the strength of the turbulence of the discs, in the literature of the satellite formation (e.g. Shibaike et al. 2017). However, the α parameter can be distinguished into two different kinds of parameters based on the physical properties: the efficiency of the angular momentum transport, $\alpha_{\rm acc}$, and the diffusion strength of dust particles, $\alpha_{\rm diff}$. The former determines the evolution of the gas accretion disc and the latter excites the motion of dust (and gas) particles (Youdin & Lithwick 2007). If $\alpha_{\rm acc}$ is high, the gas surface density is low and thereby the drift time-scale of pebble can be long. On the other hand, if $\alpha_{\rm diff}$ is low, the collision rate remains high as the particles settle on the mid-plane, provided the collision speed is not determined by the diffusion, and thus particles grow quickly. Drażkowska & Dullemond (2018) found that this is effective for the planetesimal formation in PPDs. In this paper, we investigate if it also works in the satellitesimal formation.

In the case of PPDs, the two values of α can be different when the disc is governed by the layered accretion or the magnetic wind-driven accretion. It has been considered that the most effective accretion mechanism of PPDs is the magneto-rotational instability (MRI) (Balbus & Hawley 1991, 1998). However, Gammie (1996) found that one of the non-ideal magnetohydrodynamic (MHD) effects, Ohmic resistivity prevents the MRI around the mid-plane, which is called 'dead-zone', while it is active only at the surface of the disc. In that case, the disc becomes a layered structure and the gas flows inward only at the upper layer. Okuzumi & Hirose (2011) carried out 3D ohmic-resistive MHD simulations and showed that the layered accretion occurs and $\alpha_{\rm acc} \sim 5$–$30\,\alpha_{\rm diff}$ in the inner regions of

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PPDs. On the other hand, Bai (2015) calculated 3D MHD simulations including all three non-ideal MHD effects (Ohmic resistivity, Hall effect, and ambipolar diffusion) and found that the MRI is dead not only on the mid-plane but also at the whole height of the discs.[1] Therefore, PPDs would be laminar rather than turbulent. In that case, the angular momentum is transported at the surface of the disc where the large-scale magnetic field lines are bent. This accretion mechanism is called magnetic wind-driven accretion, because gas escapes from the disc along with the magnetic field lines, which is called disc wind[2] (see also Section 2.2 for detailed explanations). Bai (2015) argued that $\alpha_{\rm acc} \gtrsim 10\,\alpha_{\rm diff}$ by a simple estimate from the outcome value of the rms vertical velocity fluctuation of the simulation results.

Most of the numerical simulations of CPDs calculated in previous works are not MHD but hydrodynamics (HD). Machida, Inutsuka & Matsumoto (2006) and Gressel et al. (2013) carried out global 3D MHD simulations of CPDs, though the former was ideal, and the latter included only Ohmic resistivity. They found that jet structures can form around the centre of the CPDs like the star formation process. In the simulation by Gressel et al. (2013), MRI is active at the surface layers of the CPDs but is dead inside the discs. It has also been considered that MRI is dead in most of the regions of CPDs other than the surfaces because of the short typical length scale of the discs (Fujii et al. 2014; Keith & Wardle 2014; Turner, Lee & Sano 2014; Fujii et al. 2017). These works calculated the Elsasser number and the plasma beta of CPDs in 1D disc models. In this work, we carry out 3D local non-ideal MHD simulations of CPDs to investigate if the discs are laminar and the magnetic wind-driven accretion dominates the disc accretion. This is the first work that carries out 3D MHD simulations of CPDs with all the non-ideal MHD effects, but the simulations are performed not in global but in local shearing boxes.

In Section 2, we perform 3D local non-ideal MHD simulations of a CPD. We consider situations where the magnetic disc wind can be launched from the disc and investigate if the disc state can be governed by the magnetic wind-driven accretion and $\alpha_{\rm acc}$ is much larger than $\alpha_{\rm diff}$. In Section 3, we calculate the evolution of dust particles in 1D CPDs modelled to be consistent with the results of the MHD simulations and investigate the condition for the satellitesimal formation. In Section 4, we estimate the region where the disc wind is launched against the vertical gas inflow ignored in the MHD simulations. We then discuss the results of MHD simulations comparing with those of the previous works. We also discuss the feasibility of the obtained condition for the satellitesimal formation; it can be reached even when the gas gap is open. We also perform the parameter studies of the satellitesimal formation. We finally conclude this work in Section 5.

2 NON-IDEAL MHD SIMULATIONS OF CPDS

2.1 Setups

We perform non-ideal MHD simulations of a CPD with an open source MHD code ATHENA[3] (Stone et al. 2008). The simulations are performed in local 3D stratified shearing boxes, reproducing four different locations in a CPD, $r = 3$, 10, 30, and 100 $R_{\rm J}$, where r is the distance from the central planet, and $R_{\rm J}$ is the Jupiter radius.

Here we put two simplifications in the CPD simulations. First, we do not set the vertical gas inflow to CPDs as the boundary condition. The inflowing boundary condition in such shearing box simulations has not been investigated well so far. In addition, the inflowing boundary condition can easily break the simulation. Such disc-wind simulations taking into account the inflow effects is a future challenge. Nevertheless, we discuss if the disc has enough potential to launch the wind even with the inflow by using the simulation results, in Section 4.1. Second, we do not consider any horizontal gas flow either, because shearing box simulations do not have the concept of inward/outward directions.

The simulation boxes are orbiting the central planet with Kepler angular velocity $\Omega_{\rm K} = \sqrt{GM_{\rm p}/r^3}$, where G is the gravitational constant and $M_{\rm p} = 1\,M_{\rm J}$ (one Jupiter mass) is the mass of the central planet. The simulations are carried out with Cartesian coordinates (x, y, z) for the radial, azimuthal, and vertical dimensions. Previous MHD simulations in the inner regions of PPDs showed that the final properties do not depend on the horizontal box sizes and resolutions (Bai & Stone 2013), and we have confirmed that it is also true in our cases. Thus, we use simulation boxes with the vertical and horizontal box sizes of $16\,H_{\rm g}$ and $0.5\,H_{\rm g}$ and the resolutions of 25 and 8 cells per $H_{\rm g}$, respectively, where $H_{\rm g}$ is the gas scale height of the CPDs. The gas scale height is $H_{\rm g} = c_{\rm s}/\Omega_{\rm K}$, where $c_{\rm s}$ is the sound speed, and $c_{\rm s} = \sqrt{k_{\rm B}T/m_{\rm g}}$, where $k_{\rm B}$, T, and $m_{\rm g} = 3.9 \times 10^{-24}$ g are the Boltzmann constant, disc temperature, and mean molecular mass, respectively.

We set the gas temperature profile of the CPD as $T = 160(r/10R_{\rm J})^{-3/4}$ K, which is consistent with the ice mass fractions of the Galilean satellites (e.g. Kuskov & Kronrod 2005), and assume the gas is isothermal in each simulation box. Although the assumed temperature is lower than that of turbulent discs, we note that the heating can occur at high altitude in magnetic wind-driven accretion discs, and the mid-plane temperature can be lower (Mori, Bai & Okuzumi 2019). As the initial conditions, we set the gas surface density as $\Sigma_{\rm g} = 1000(r/10R_{\rm J})^{-3/4}\,{\rm g\,cm^{-2}}$ (see Section 4.2 for the reason why we choose this profile) and the density distribution in hydrostatic equilibrium. We fix the dust-to-gas ratio of 0.1 µm-sized dust particles as $f_{\rm dg} = 1 \times 10^{-6}$.

We also set the initial magnetic field as $\boldsymbol{B}_0 = (0, 0, B_0)$, where B_0 is characterized by a parameter $\beta_0 = 8\pi\rho_{\rm g,0}c_{\rm s}^2/B_0^2$, which is assumed as $\beta_0 = 10^5$ in this work. Depending on the direction of B_0, the Hall effect amplifies or damps the magnetic field. We here take B_0 to be aligned with the disc rotation vector, in which the magnetic field is amplified by the Hall effect.

We give the magnetic diffusivities of the non-ideal MHD effects with calculating the balance between the ionization and recombination, basically following Mori et al. (2019). The magnetic diffusivities depend on the number densities of charged particles (electrons, ions, and charged dust particles). The ionization sources are cosmic rays, stellar X-rays, and radionuclides. The cosmic ray ionization rate profile is described in Sano et al. (2000) which is based on Umebayashi & Nakano (1981). The ionization rate of the X-ray follows the fitting formula consistent with Igea & Glassgold (1999) and Bai & Goodman (2009), but we neglect components that directly reach the disc surface. We set the X-ray temperature to be 5 keV and the X-ray luminosity to be $2 \times 10^{30}\,{\rm erg\,s^{-1}}$. Also, the location of the CPD is assumed to be 5.2 au from the protosun. The latter is the median value of the luminosity of the Solar-mass stars in the Orion Nebula Cluster (Garmire et al.

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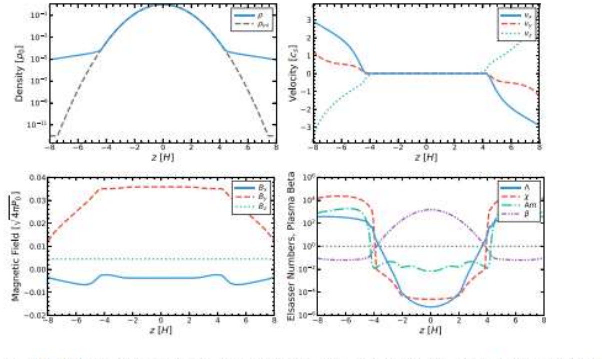

Figure 1. Vertical profiles of the temporal and horizontal average for a representative run at $r = 10\,R_{\rm J}$. Upper left: gas density at the final state (ρ, solid) and initial state ($\rho_{\rm ini}$, dashed), normalized by the initially set density on the mid-plane, ρ_0. Upper right: three components of the gas velocity (v_x, v_y, v_z). Lower left: three components of the magnetic field. Lower right: Elsasser numbers for Ohmic resistivity (Λ), Hall effect (χ), ambipolar diffusion (Am), and plasma beta (β).

2000). The radionuclide ionization rate is set as a constant value of $7.6 \times 10^{-19}\,{\rm s^{-1}}$ (Umebayashi & Nakano 2008). We consider the recombination in gas phase and on dust particles, where we represent ions and ionized dust particles by a single species. We limit the total diffusivities to $300\,c_{\rm s}H_{\rm g}$ to avoid the calculation time step to be too short.

We also consider the ionization by far-ultraviolet radiation (FUV) above its penetration depth. The stellar FUV rays are scattered around the wall of the gaps and partially enters the CPDs, which is reduced to 4 per cent of the stellar luminosity (Turner et al. 2012). We assume the stellar FUV luminosity as $2 \times 10^{31}\,{\rm erg\,s^{-1}}$, and so the FUV flux reaches to the CPDs is equivalent to the luminosity of $8 \times 10^{29}\,{\rm erg\,s^{-1}}$. The stellar FUV luminosity is set as a higher value than that of the current sun because it should have been higher in the past (e.g. Yang & Krumholz 2012). The penetration depth is then about $0.03\,{\rm g\,cm^{-2}}$, following the ionization models in Perez-Becker & Chiang (2011). We obtain the ionization fraction of 3×10^{-5} in the FUV layer with a similar treatment used in Bai & Stone (2013).

2.2 Results

2.2.1 Magnetic disc wind of CPDs

The obtained results of the four simulations at the different places are qualitatively similar, so we focus on the simulation results at $r = 10\,R_{\rm J}$. Fig. 1 represents the vertical profiles of the density, velocity, and magnetic fields of the simulation result. These are the temporal and horizontal average over the last 10 orbits of the total 50 orbits. However, after the vertical profiles reach these states shown in the figure, the profiles are almost steady and have only small variation. These vertical profiles are like those of PPDs with wind-driven accretion (e.g. Bai & Stone 2013).

The upper two panels of Fig. 1 show that the magnetic disc wind is launched from the surfaces of the CPD ($|z| = 4\,H_{\rm g}$). At $|z| > 4\,H_{\rm g}$, the density profile deviates from the equilibrium profile given as the initial profile (upper left panel) and the gas flows out vertically (upper right). This is explained by the behaviour of the magnetic field (lower left). The gas is pushed up to the surfaces of the CPD by the toroidal magnetic field amplified at $|z| < 4\,H_{\rm g}$. The gas then gains angular momentum via the poloidal field threading the disc around its surfaces, thereby flowing away as the disc wind. The disc wind is launched continuously in this situation.

The magnetic field profile can be explained by the Elsasser numbers of the diffusivities (lower right). The Elsasser number of a diffusivity η is defined as

$$\Lambda = \frac{v_{\rm A}^2}{\Omega_{\rm K}\eta}, \tag{1}$$

where $v_{\rm A}$ is the Alfvén speed. When the Elsasser number is less than unity, the non-ideal MHD effects are stronger than the magnetic induction due to the shear flow. Around the mid-plane, the Ohmic diffusion is the dominant MHD process. Perturbations of magnetic field are quickly diffused, and so the magnetic field is constant. In addition, ambipolar diffusion dominates over the magnetic induction within $4\,H_{\rm g}$. For these reasons, the MRI turbulence is fully suppressed below $4\,H_{\rm g}$, and therefore the CPD is laminar. Nevertheless, the Hall effect at $z = 2$–$4\,H_{\rm g}$ amplifies the magnetic field with the shear flow (i.e. Hall-shear instability; Kunz 2008). The amplified toroidal field diffuses into the CPD, so that the magnetic field is still strong even in the disc.

2.2.2 Magnetic wind-driven accretion

The disc wind flowing out from the surfaces of CPDs takes the disc angular momentum from the gas around the surfaces. The gas

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[1] Bai & Stone (2013) also found that the MRI is dead at the whole height of PPDs by MHD simulations including Ohmic resistivity and ambipolar diffusion.

[2] The word 'disc wind' is used for general mass-loss from PPDs, and it launches not only from magnetic wind-driven accretion discs but also from MRI turbulent discs (Suzuki et al. 2016).

[3] https://princetonuniversity.github.io/Athena-Cversion/

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GLOBAL HYDROMAGNETIC SIMULATIONS OF A PLANET EMBEDDED IN A DEAD ZONE: GAP OPENING, GAS ACCRETION, AND FORMATION OF A PROTOPLANETARY JET

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ABSTRACT

We present global hydrodynamic (HD) and magnetohydrodynamic (MHD) simulations with mesh refinement of accreting planets embedded in protoplanetary disks (PPDs). The magnetized disk includes Ohmic resistivity that depends on the overlying mass column, leading to turbulent surface layers and a dead zone near the midplane. The main results are: (1) the accretion flow in the Hill sphere is intrinsically three-dimensional for HD and MHD models. Net inflow toward the planet is dominated by high-latitude flows. A circumplanetary disk (CPD) forms. Its midplane flows outward in a pattern whose details differ between models. (2) The opening of a gap magnetically couples and ignites the dead zone near the planet, leading to stochastic accretion, a quasi-turbulent flow in the Hill sphere, and a CPD whose structure displays high levels of variability. (3) Advection of magnetized gas onto the rotating CPD generates helical fields that launch magnetocentrifugally driven outflows. During one specific epoch, a highly collimated, one-sided jet is observed. (4) The CPD's surface density is $\sim 30\,\mathrm{g\,cm^{-2}}$, small enough for significant ionization and turbulence to develop. (5) The accretion rate onto the planet in the MHD simulation reaches a steady value $8 \times 10^{-3}\,M_{\oplus}\,\mathrm{yr}^{-1}$ and is similar in the viscous HD runs. Our results suggest that gas accretion onto a forming giant planet within a magnetized PPD with a dead zone allows rapid growth from Saturnian to Jovian masses. As well as being relevant for giant planet formation, these results have important implications for the formation of regular satellites around gas giant planets.

Key words: magnetohydrodynamics (MHD) – methods: numerical – planets and satellites: formation – protoplanetary disks

Online-only material: color figures

1. INTRODUCTION

Gas giant planets are widely believed to form via core nucleated accretion, a scenario that begins with the formation of a solid rock and ice core in a protoplanetary disk (PPD) by the agglomeration of smaller bodies (planetesimals) and which concludes with the accretion of a gaseous envelope from the surrounding nebula (Mizuno 1980). Although it has been suggested that giant planets may form through the direct gravitational fragmentation of a massive PPD during its early evolution (Boss 1998), circumstantial evidence for core accretion having operated in the solar system is provided by the inferred existence of significant cores in Saturn, Uranus, (e.g., Saumon & Guillot 2004) and Neptune. It can further be argued that the substantial numbers of relatively low-mass super-Earth and Neptune-like extrasolar planets being discovered (e.g., Lissauer et al. 2011) indicate that core accretion is a common mode of planetary formation outside of the solar system.

Detailed one-dimensional (1D) models of gas giant planet formation indicate that envelope accretion occurs in two distinct stages: (1) a quasi-static contraction phase during which the envelope mass grows slowly over timescales $\gtrsim 1$ Myr (Pollack et al. 1996) and (2) a runaway growth phase during which the envelope accretes dynamically onto the planet. This later phase normally arises once the envelope exceeds the core mass, corresponding to a total planet mass $\gtrsim 35\,M_{\oplus}$. Prior to runaway gas accretion, the protoplanet remains embedded in the nebula and the bloated envelope is envisaged to connect smoothly onto the surrounding disk. During the runaway phase, however, the planet contracts down to a size $\simeq 3$ Jupiter radii and gas accreti
is expected to occur through a circumplanetary disk (CPD) t
forms by the flow of gas into the planet Hill sphere (Papaloiz
& Nelson 2005). We note that the 1D envelope calculatio
indicate that planets with Saturn-like masses ($\sim$0.2–0.6 M
are likely to experience maximal gas accretion (Pollack et
1996), as the flow onto the planet is relatively unimpeded
the compressional heating of the envelope for these mass
Although these 1D quasi-static calculations cannot determi
the details of the hydrodynamic (HD) flow, so some dou
remains about the actual accretion rate, it is noteworthy t
extrasolar planets with masses similar to Saturn are commo
even though existing calculations suggest that once a pla
enters the runaway gas-accretion phase it should grow rapi
beyond this mass if it is in the presence of a signific
gas reservoir. One motivation for performing the calculatio
presented in this paper is to address this issue and to exami
whether or not a possible bottleneck exists that can prevent ra
growth of planets in this mass range.

The formation of a gas giant planet through gas accretion a
the action of tidal torques lead to the formation of an annu
gap around the vicinity of the planet (Lin & Papaloizou 19
Bryden et al. 1999; Kley 1999; Lubow et al. 1999). This m
also herald the transition of the planet's migration from ty
I (Ward 1997) during the embedded phase to type II whe
gap has formed (Lin & Papaloizou 1986; Nelson et al. 200
Material then feeds onto the planet through the gap at the visc

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[5] Out of 720 confirmed extrasolar planets listed on `exoplanets.org`, approximately 170 have masses in the range 0.2–1 M_J.

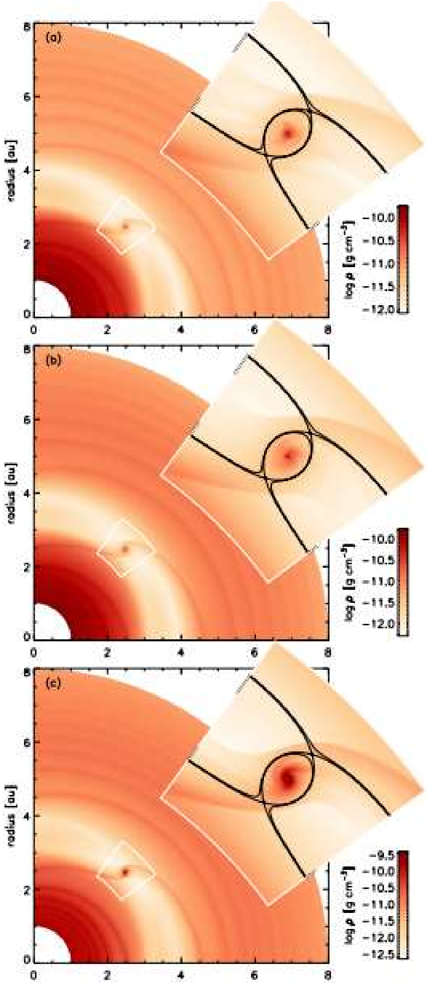

Figure 1. Midplane slices of $\log(\rho)$. From top to bottom: (a) MHD run, (b) HD run with cooling, (c) isothermal HD run. Black contours indicate the potential surfaces passing through the Lagrange points L1 and L2.

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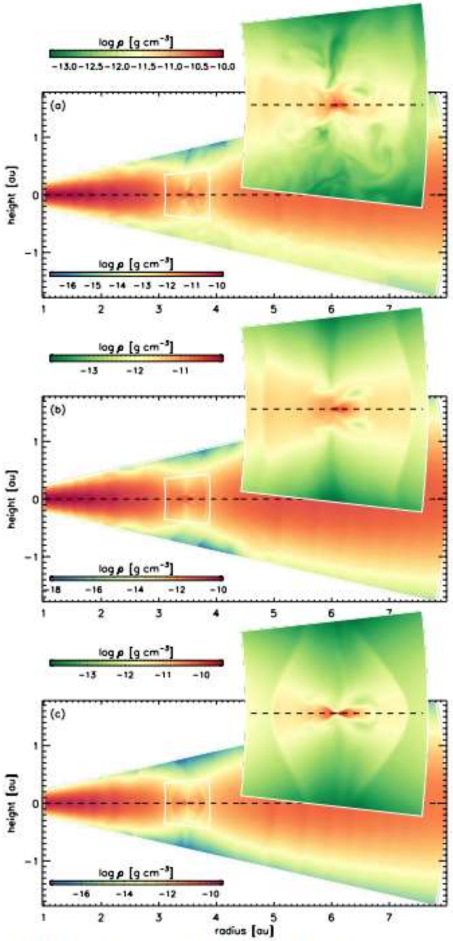

Figure 2. Meridional plane showing $\log(\rho)$ at the planet location (note the separate color bars for the insets). From top to bottom: (a) MHD run, (b) HD run with cooling, (c) isothermal HD run. Underdense layers above and below the CPD are related to pairs of poloidal vortices.

(A color version of this figure is available in the online journal.)

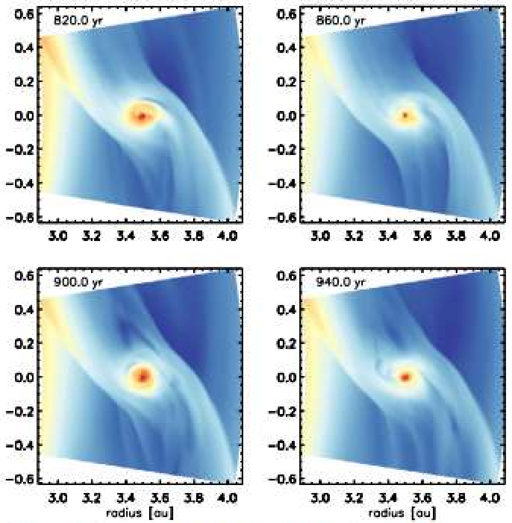

Figure 12. Similar to Figure 11, but for midplane slices of the gas density.

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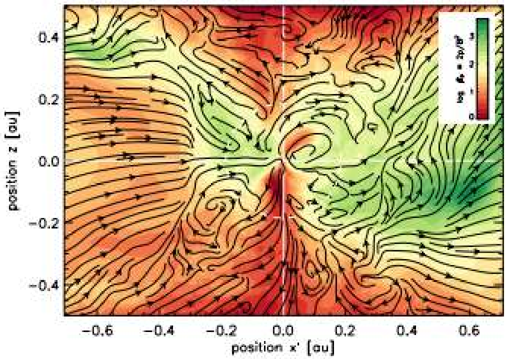
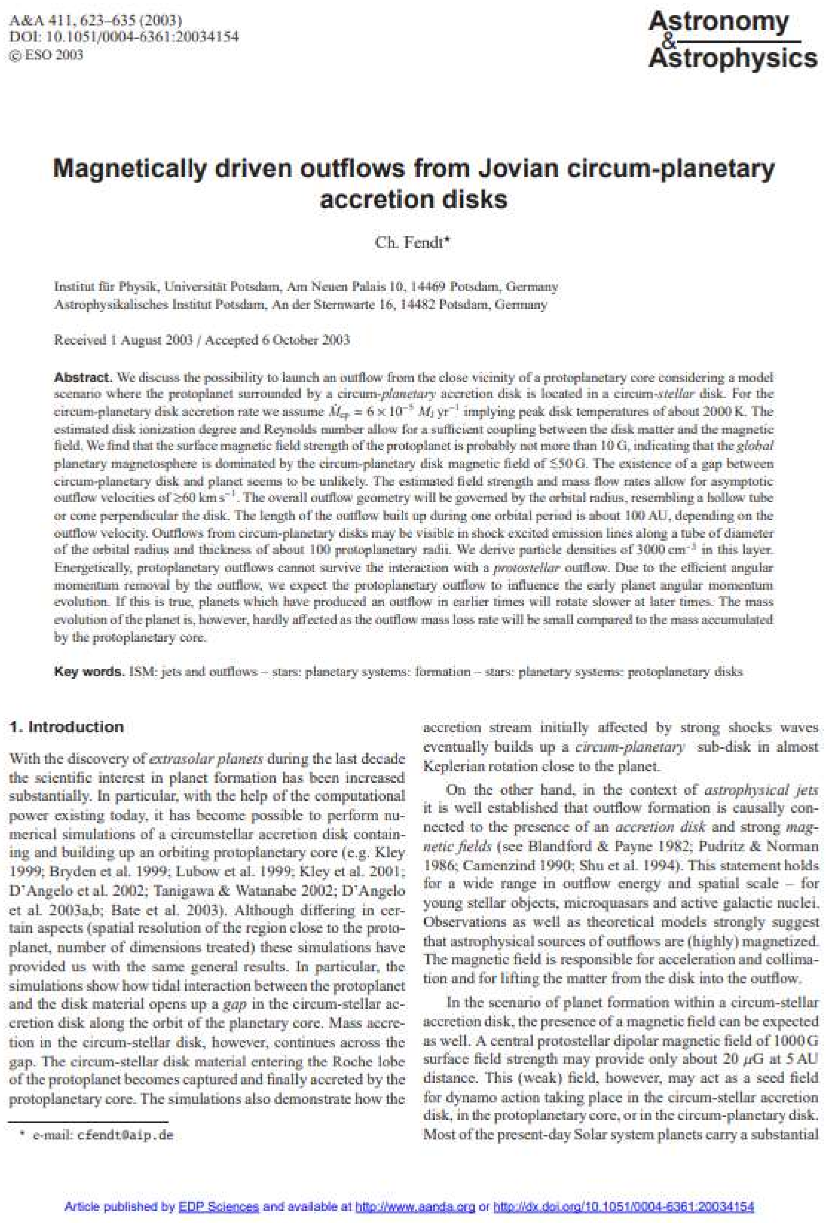


Figure 13. Radial–vertical slice of the logarithm of the plasma parameter, $\beta_P \equiv 2p/B^2$, and projected magnetic field lines. Averages are taken over eight planet orbits at the time corresponding to the last panel in Figure 11.

(A color version of this figure is available in the online journal.)



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Astronomy & Astrophysics

Magnetically driven outflows from Jovian circum-planetary accretion disks

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Abstract. We discuss the possibility to launch an outflow from the close vicinity of a protoplanetary core considering a model scenario where the protoplanet surrounded by a circum-*planetary* accretion disk is located in a circum-*stellar* disk. For the circum-planetary disk accretion rate we assume $\dot{M}_{\rm cp} = 6 \times 10^{-5}\, M_{\rm J}\, {\rm yr}^{-1}$ implying peak disk temperatures of about 2000 K. The estimated disk ionization degree and Reynolds number allow for a sufficient coupling between the disk matter and the magnetic field. We find that the surface magnetic field strength of the protoplanet is probably not more than 10 G, indicating that the *global* planetary magnetosphere is dominated by the circum-planetary disk magnetic field of ≤ 50 G. The existence of a gap between circum-planetary disk and planet seems to be unlikely. The estimated field strength and mass flow rates allow for asymptotic outflow velocities of $\geq 60\,{\rm km\,s^{-1}}$. The overall outflow geometry will be governed by the orbital radius, resembling a hollow tube or cone perpendicular the disk. The length of the outflow built up during one orbital period is about 100 AU, depending on the outflow velocity. Outflows from circum-planetary disks may be visible in shock excited emission lines along a tube of diameter of the orbital radius and thickness of about 100 protoplanetary radii. We derive particle densities of $3000\,{\rm cm^{-3}}$ in this layer. Energetically, protoplanetary outflows cannot survive the interaction with a *protostellar* outflow. Due to the efficient angular momentum removal by the outflow, we expect the protoplanetary outflow to influence the early planet angular momentum evolution. If this is true, planets which have produced an outflow in earlier times will rotate slower at later times. The mass evolution of the planet is, however, hardly affected as the outflow mass loss rate will be small compared to the mass accumulated by the protoplanetary core.

Key words. ISM: jets and outflows – stars: planetary systems: formation – stars: planetary systems: protoplanetary disks

1. Introduction

With the discovery of *extrasolar planets* during the last decade the scientific interest in planet formation has been increased substantially. In particular, with the help of the computational power existing today, it has become possible to perform numerical simulations of a circumstellar accretion disk containing and building up an orbiting protoplanetary core (e.g. Kley 1999; Bryden et al. 1999; Lubow et al. 1999; Kley et al. 2001; D'Angelo et al. 2002; Tanigawa & Watanabe 2002; D'Angelo et al. 2003a,b; Bate et al. 2003). Although differing in certain aspects (spatial resolution of the region close to the protoplanet, number of dimensions treated) these simulations have provided us with the same general results. In particular, the simulations show how tidal interaction between the protoplanet and the disk material opens up a *gap* in the circum-stellar accretion disk along the orbit of the planetary core. Mass accretion in the circum-stellar disk, however, continues across the gap. The circum-stellar disk material entering the Roche lobe of the protoplanet becomes captured and finally accreted by the protoplanetary core. The simulations also demonstrate how the accretion stream initially affected by strong shocks waves eventually builds up a *circum-planetary* sub-disk in almost Keplerian rotation close to the planet.

On the other hand, in the context of *astrophysical jets* it is well established that outflow formation is causally connected to the presence of an *accretion disk* and strong *magnetic fields* (see Blandford & Payne 1982; Pudritz & Norman 1986; Camenzind 1990; Shu et al. 1994). This statement holds for a wide range in outflow energy and spatial scale – for young stellar objects, microquasars and active galactic nuclei. Observations as well as theoretical models strongly suggest that astrophysical sources of outflows are (highly) magnetized. The magnetic field is responsible for acceleration and collimation and for lifting the matter from the disk into the outflow.

In the scenario of planet formation within a circum-stellar accretion disk, the presence of a magnetic field can be expected as well. A central protostellar dipolar magnetic field of 1000 G surface field strength may provide only about 20 μG at 5 AU distance. This (weak) field, however, may act as a seed field for dynamo action taking place in the circum-stellar accretion disk, in the protoplanetary core, or in the circum-planetary disk. Most of the present-day Solar system planets carry a substantial

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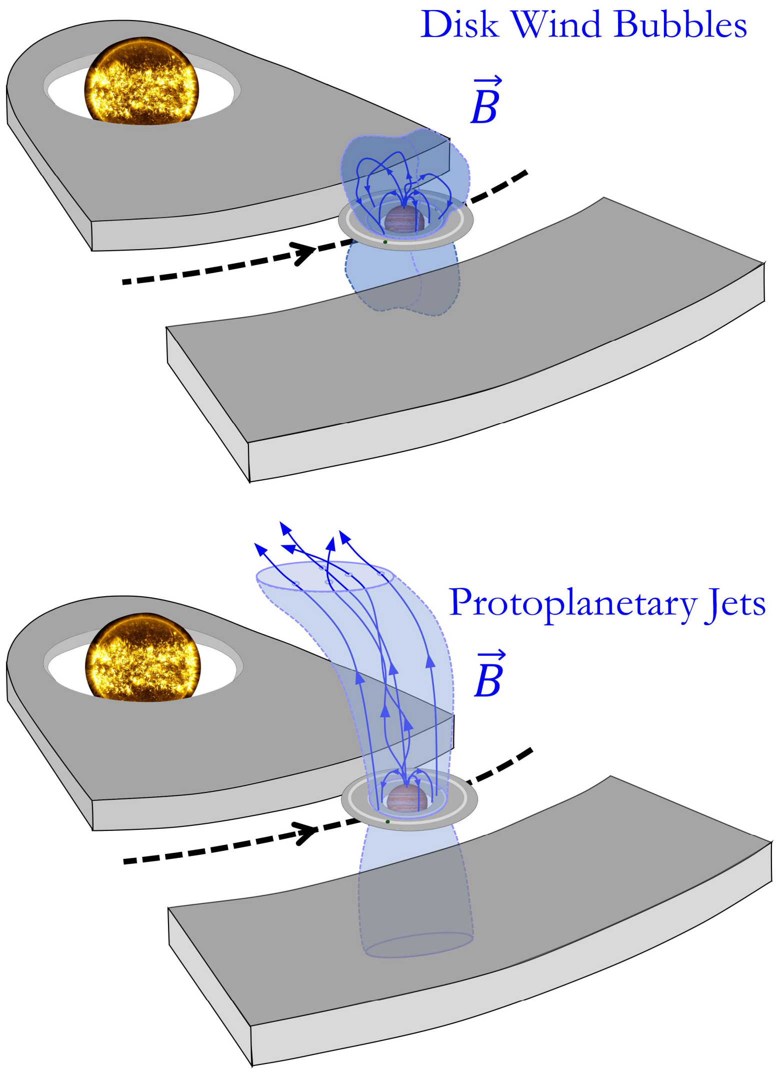
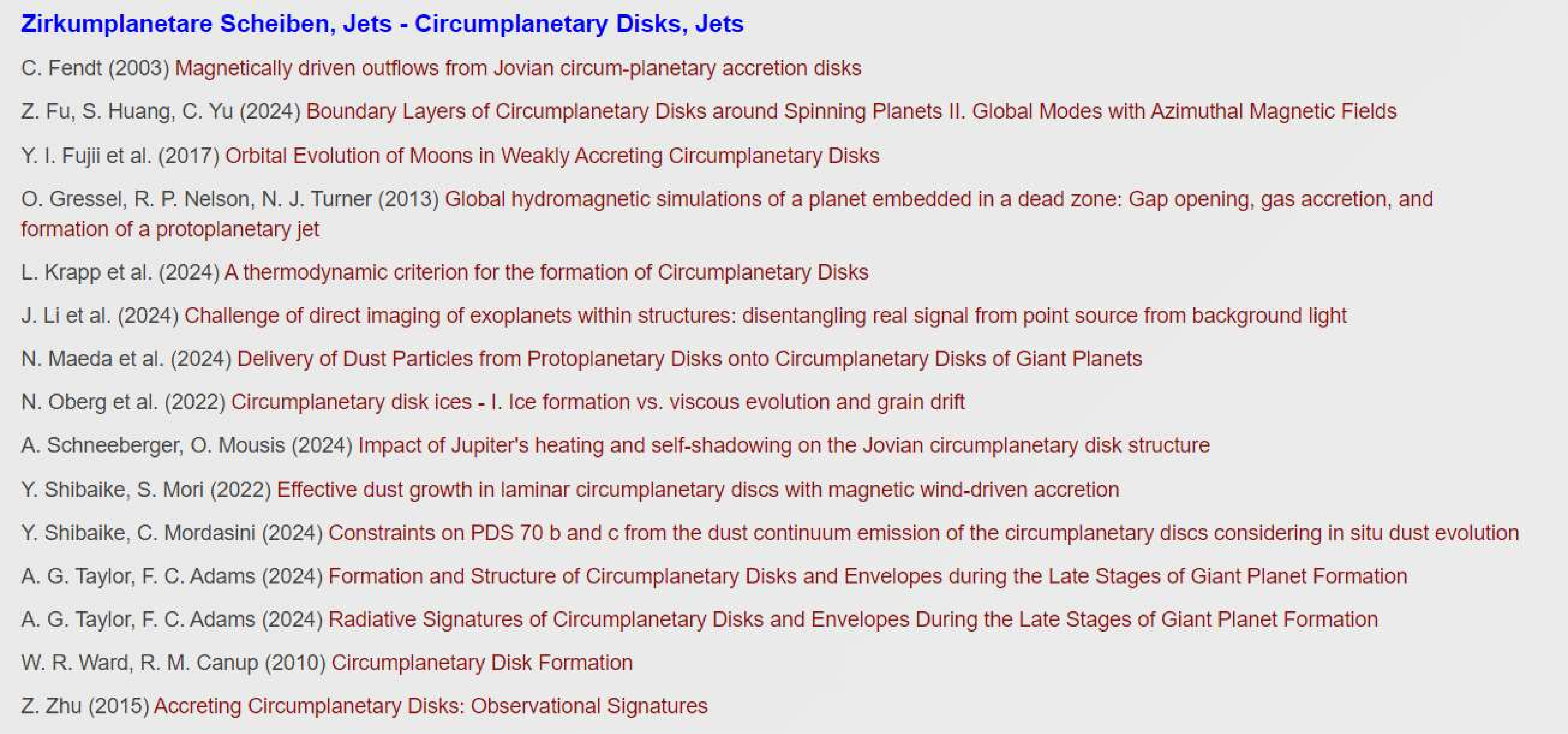


Magnetized protoplanetary disk winds - U. v. Kusserow/C. Fendt (2023)

Entstehung des magnetischen Sonnensystems Formation of the magnetic Solar System



Zirkumplanetare Scheiben, Jets - Circumplanetary Disks, Jets

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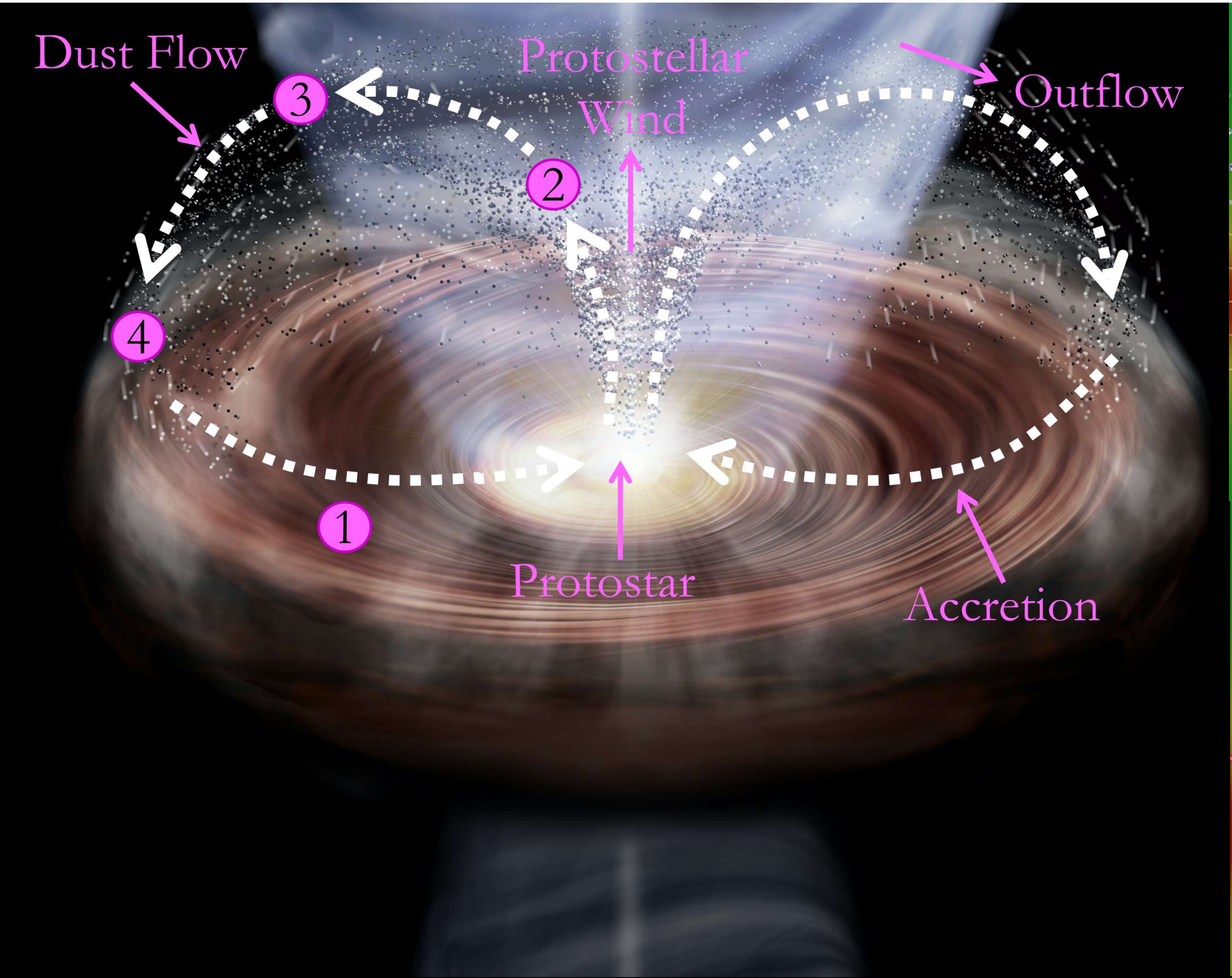
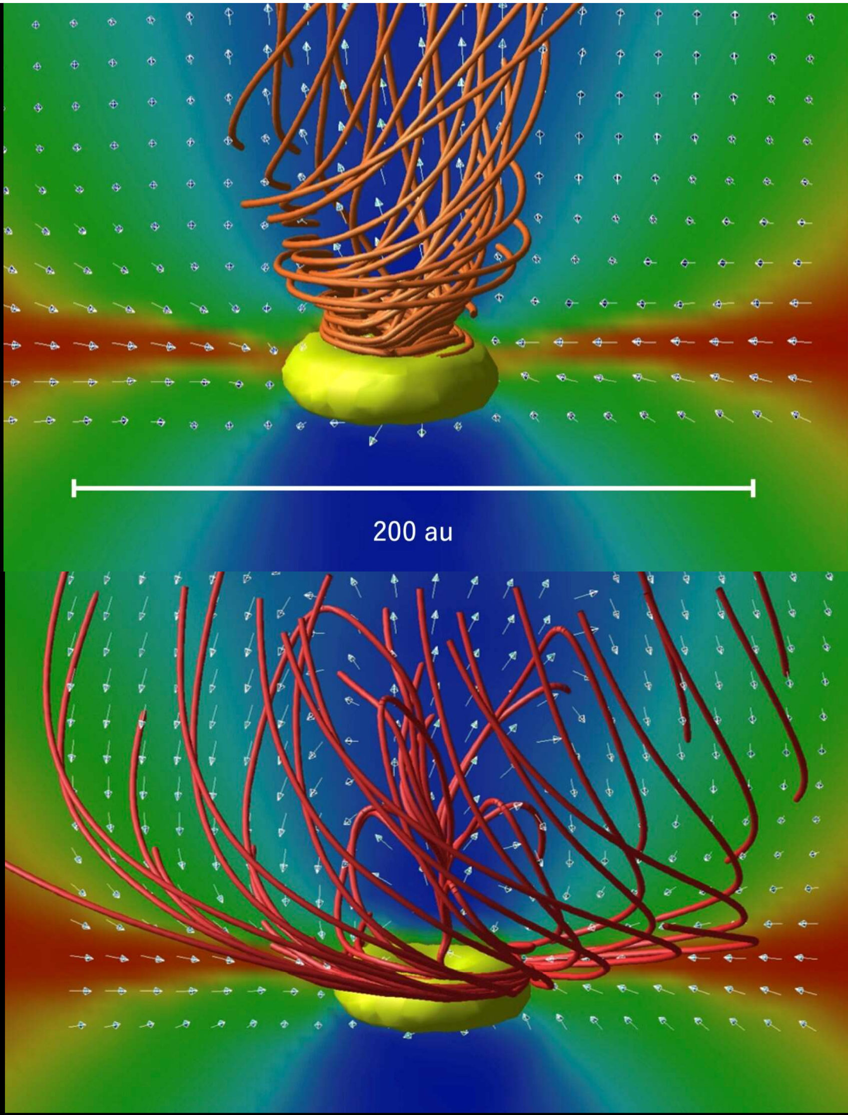
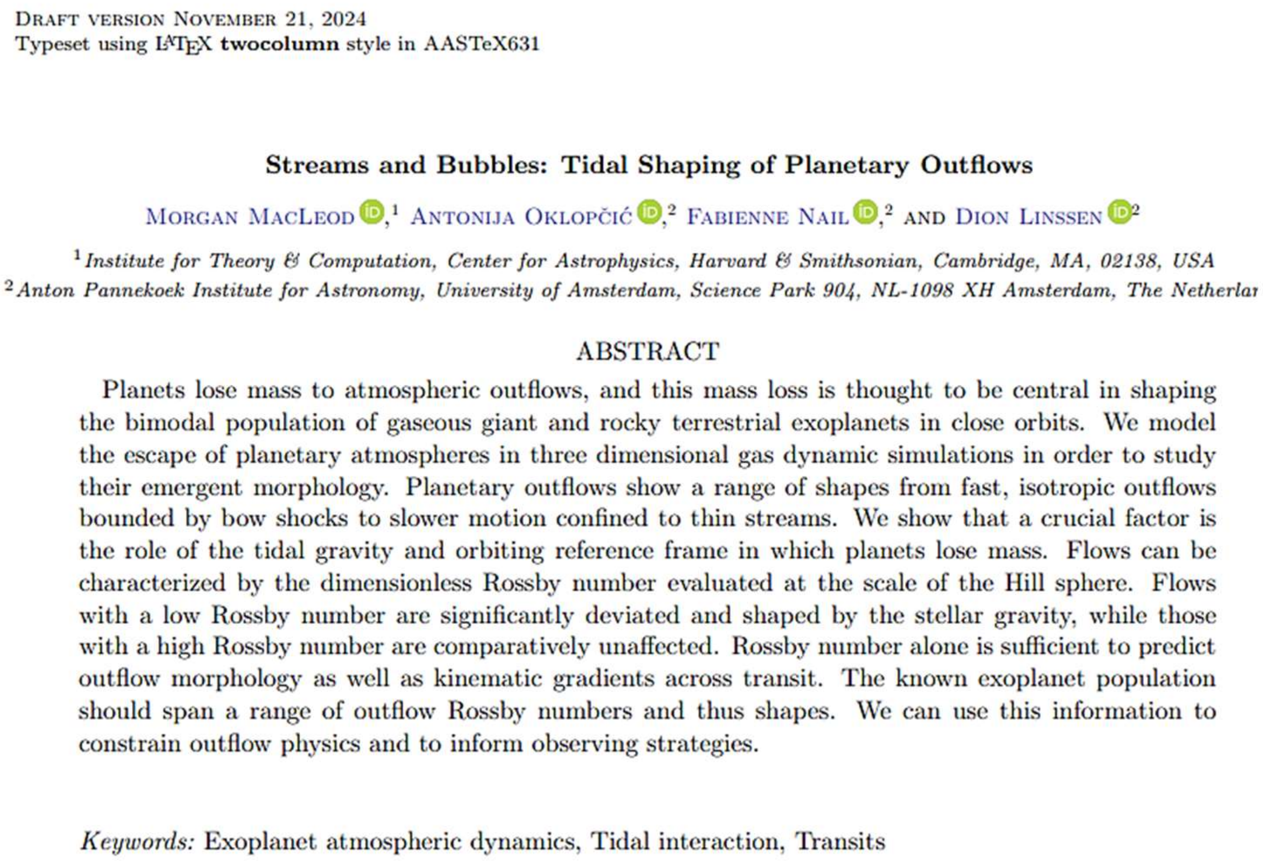

Dust Flow
③
Protostellar Wind
Outflow
②
④
①
Protostar
Accretion

“Ash rain” drifting outwards above the accretion disk near the protostar, driven by matter ejection in protostellar winds

Y. Tsukamoto/Kagoshima University, M. N. Machida, S. Inutsuka (Editing: U. v. Kusserow)



Results of simulation calculations: electrically charged particles are preferentially transported poleward due to their binding to the magnetic fields in collimated protostellar jet streams (above), neutral particles drift more strongly outwards because of centrifugal forces (below)



Draft version November 21, 2024
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Streams and Bubbles: Tidal Shaping of Planetary Outflows

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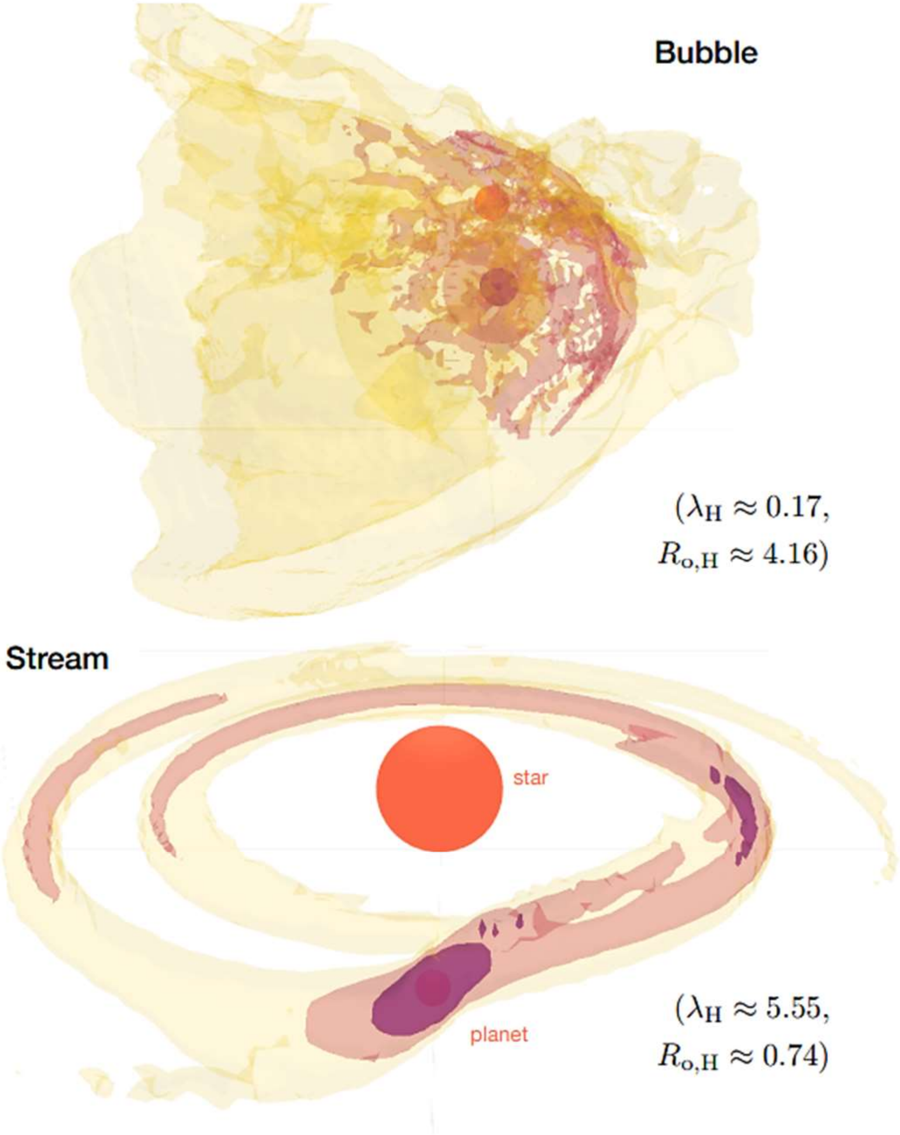
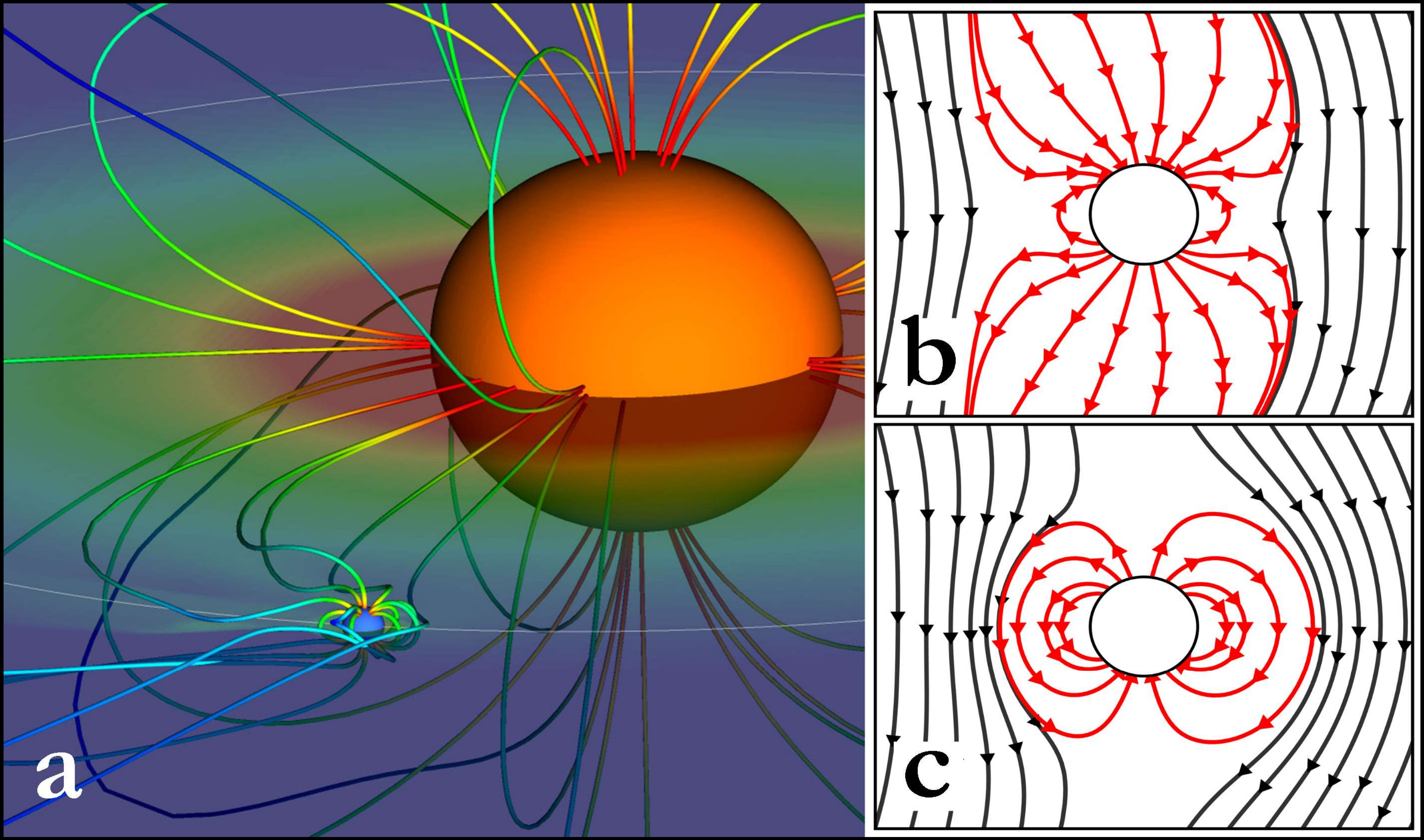
[2] *Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, NL-1098 XH Amsterdam, The Netherla*

ABSTRACT

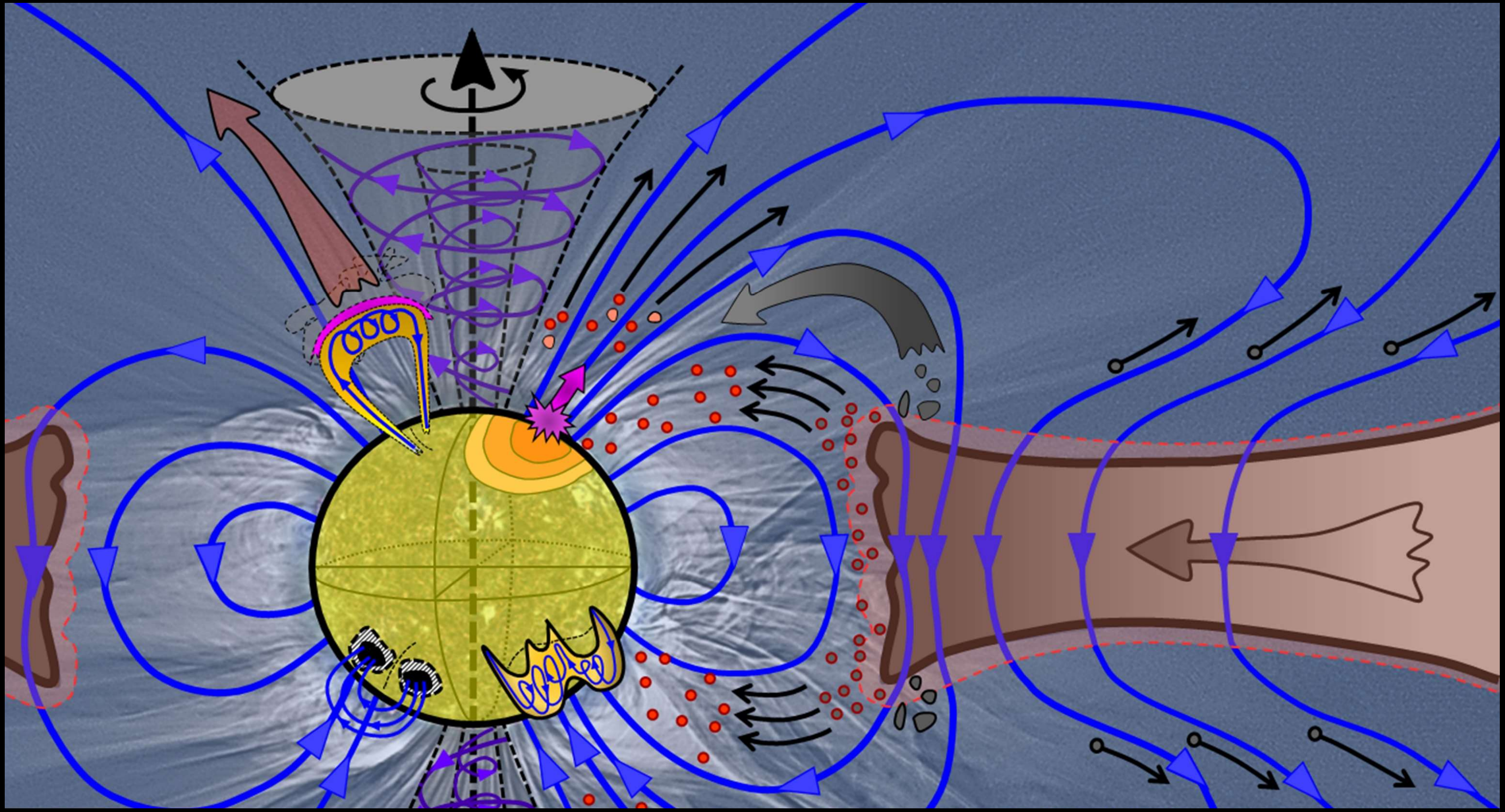
Planets lose mass to atmospheric outflows, and this mass loss is thought to be central in shaping the bimodal population of gaseous giant and rocky terrestrial exoplanets in close orbits. We model the escape of planetary atmospheres in three dimensional gas dynamic simulations in order to study their emergent morphology. Planetary outflows show a range of shapes from fast, isotropic outflows bounded by bow shocks to slower motion confined to thin streams. We show that a crucial factor is the role of the tidal gravity and orbiting reference frame in which planets lose mass. Flows can be characterized by the dimensionless Rossby number evaluated at the scale of the Hill sphere. Flows with a low Rossby number are significantly deviated and shaped by the stellar gravity, while those with a high Rossby number are comparatively unaffected. Rossby number alone is sufficient to predict outflow morphology as well as kinematic gradients across transit. The known exoplanet population should span a range of outflow Rossby numbers and thus shapes. We can use this information to constrain outflow physics and to inform observing strategies.

Keywords: Exoplanet atmospheric dynamics, Tidal interaction, Transits


Bubble
$(\lambda_{\rm H} \approx 0.17,$
$R_{\rm o,H} \approx 4.16)$
Stream
star
planet
$(\lambda_{\rm H} \approx 5.55,$
$R_{\rm o,H} \approx 0.74)$

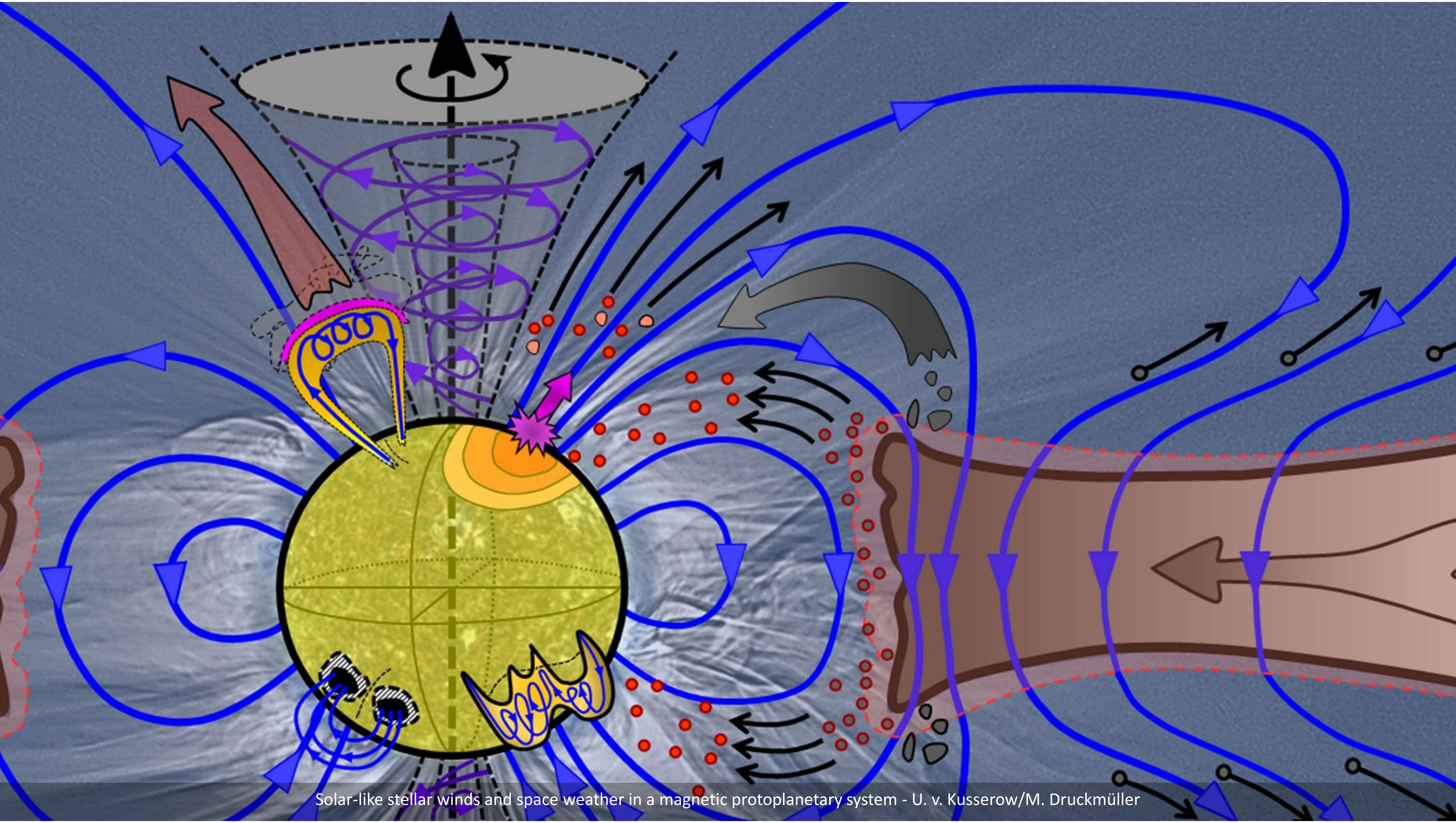


Interaction of stellar and planetary magnetic fields (a). Based on the results of computer simulations, different magnetic field topologies arise in the vicinity of the planets depending on the relative orientation of stellar and planetary fields to each other (b and c) - A. Strugarek, compilation: U. v. Kusserow

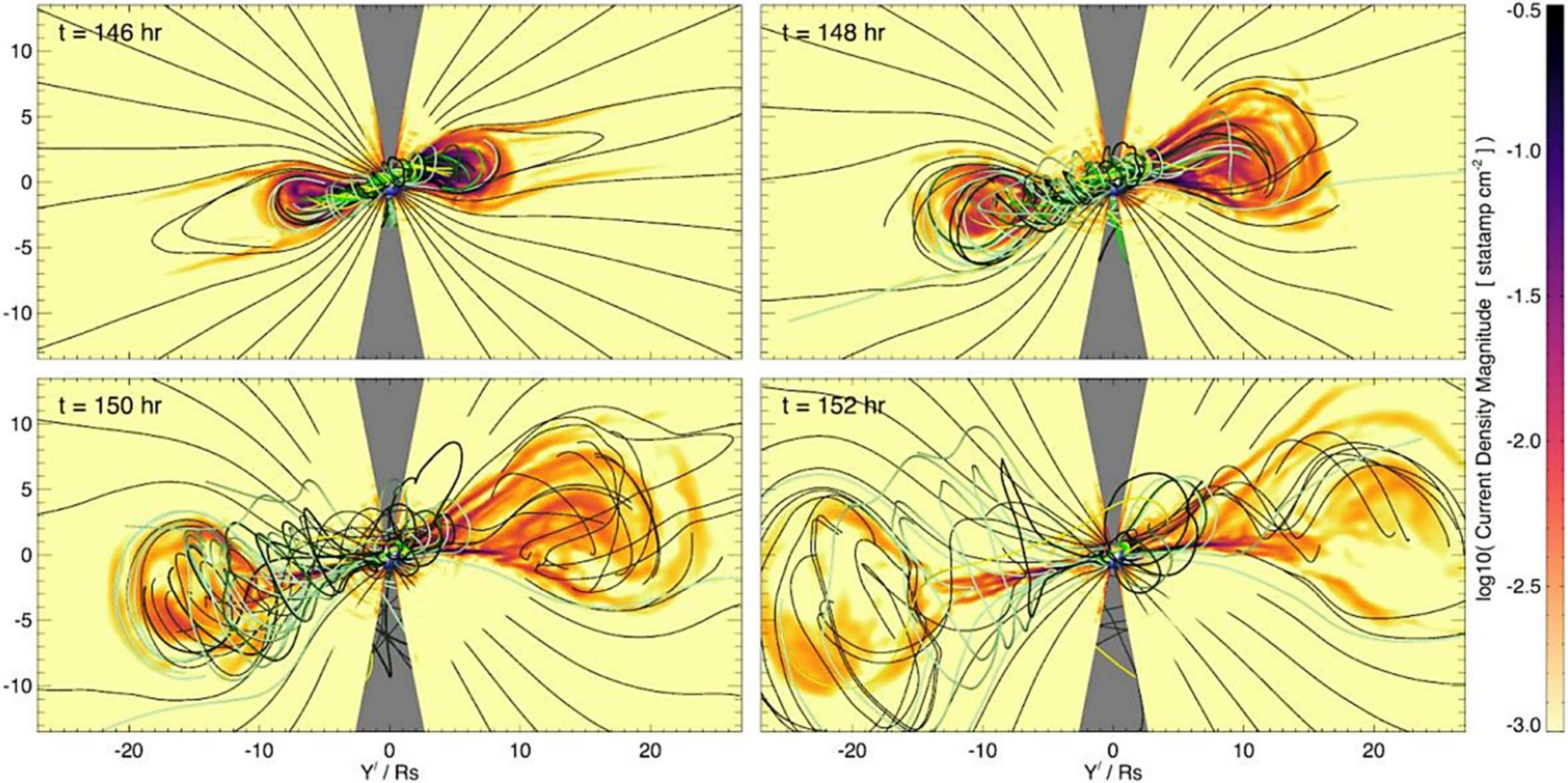


$$\frac{\partial \vec{\boldsymbol{B}}}{\partial \boldsymbol{t}} = \vec{\boldsymbol{\nabla}} \times (\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}}) - \vec{\boldsymbol{\nabla}} \times (\eta_{\mathrm{OD}} \cdot \vec{\boldsymbol{\nabla}} \times \vec{\boldsymbol{B}}) + \vec{\boldsymbol{\nabla}} \times \{\eta_{\mathrm{AD}} \cdot (\vec{\boldsymbol{\nabla}} \times \vec{\boldsymbol{B}}) \times \vec{\boldsymbol{B}}\} - \vec{\boldsymbol{\nabla}} \times [\vec{\boldsymbol{\nabla}} \times \{\eta_{\mathrm{HD}} \cdot (\vec{\boldsymbol{\nabla}} \times \vec{\boldsymbol{B}}) \times \vec{\boldsymbol{B}}\}]$$

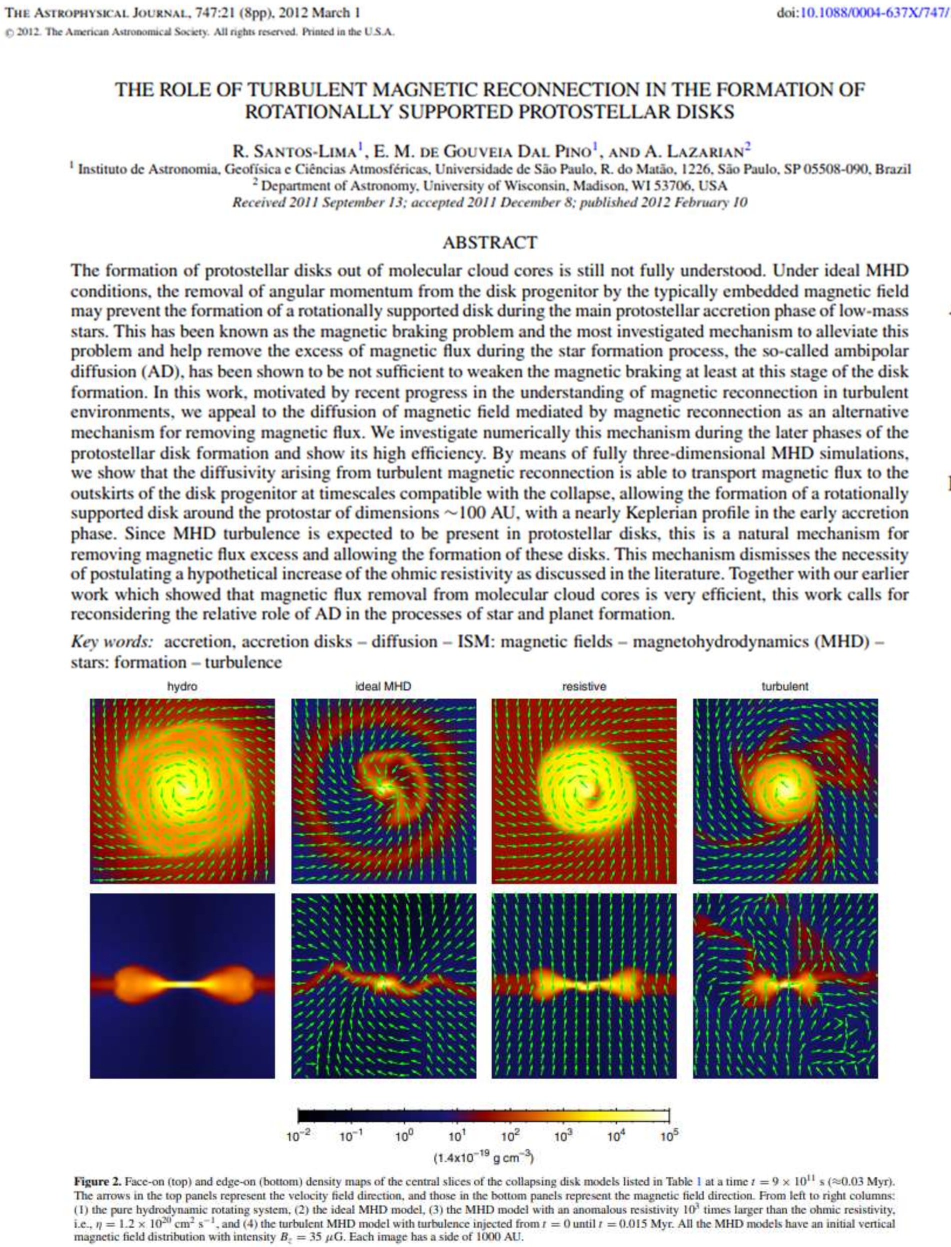
Future Significance



Solar-like stellar winds and space weather in a magnetic protoplanetary system - U. v. Kusserow/M. Druckmüller



3D simulation of a massive (Carrington scale) stellar coronal eruption initiated from a magnetogram - B. J. Lynch et al. (2019)



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THE ROLE OF TURBULENT MAGNETIC RECONNECTION IN THE FORMATION OF ROTATIONALLY SUPPORTED PROTOSTELLAR DISKS

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ABSTRACT

The formation of protostellar disks out of molecular cloud cores is still not fully understood. Under ideal MHD conditions, the removal of angular momentum from the disk progenitor by the typically embedded magnetic field may prevent the formation of a rotationally supported disk during the main protostellar accretion phase of low-mass stars. This has been known as the magnetic braking problem and the most investigated mechanism to alleviate this problem and help remove the excess of magnetic flux during the star formation process, the so-called ambipolar diffusion (AD), has been shown to be not sufficient to weaken the magnetic braking at least at this stage of the disk formation. In this work, motivated by recent progress in the understanding of magnetic reconnection in turbulent environments, we appeal to the diffusion of magnetic field mediated by magnetic reconnection as an alternative mechanism for removing magnetic flux. We investigate numerically this mechanism during the later phases of the protostellar disk formation and show its high efficiency. By means of fully three-dimensional MHD simulations, we show that the diffusivity arising from turbulent magnetic reconnection is able to transport magnetic flux to the outskirts of the disk progenitor at timescales compatible with the collapse, allowing the formation of a rotationally supported disk around the protostar of dimensions ~100 AU, with a nearly Keplerian profile in the early accretion phase. Since MHD turbulence is expected to be present in protostellar disks, this is a natural mechanism for removing magnetic flux excess and allowing the formation of these disks. This mechanism dismisses the necessity of postulating a hypothetical increase of the ohmic resistivity as discussed in the literature. Together with our earlier work which showed that magnetic flux removal from molecular cloud cores is very efficient, this work calls for reconsidering the relative role of AD in the processes of star and planet formation.

Key words: accretion, accretion disks – diffusion – ISM: magnetic fields – magnetohydrodynamics (MHD) – stars: formation – turbulence

Figure 2. Face-on (top) and edge-on (bottom) density maps of the central slices of the collapsing disk models listed in Table 1 at a time $t = 9 \times 10^{11}$ s (≈0.03 Myr). The arrows in the top panels represent the velocity field direction, and those in the bottom panels represent the magnetic field direction. From left to right columns: (1) the pure hydrodynamic rotating system, (2) the ideal MHD model, (3) the MHD model with an anomalous resistivity 10^3 times larger than the ohmic resistivity, i.e., $\eta = 1.2 \times 10^{20}$ cm^2 s^{-1}, and (4) the turbulent MHD model with turbulence injected from $t = 0$ until $t = 0.015$ Myr. All the MHD models have an initial vertical magnetic field distribution with intensity $B_z = 35\ \mu$G. Each image has a side of 1000 AU.

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Preprint typeset using LaTeX style emulateapj v. 01/23/15

APPLICATIONS OF FAST MAGNETIC RECONNECTION MODELS TO THE ATMOSPHERES OF THE SUN AND PROTOPLANETARY DISKS

Fulvia Pucci[1], K. Alkendra P. Singh[2,3], Uma Gorti[4,5], Marco Velli[6], Neal J. Turner[1], Disha Varshney[2], Maria Elena Innocenti[7]
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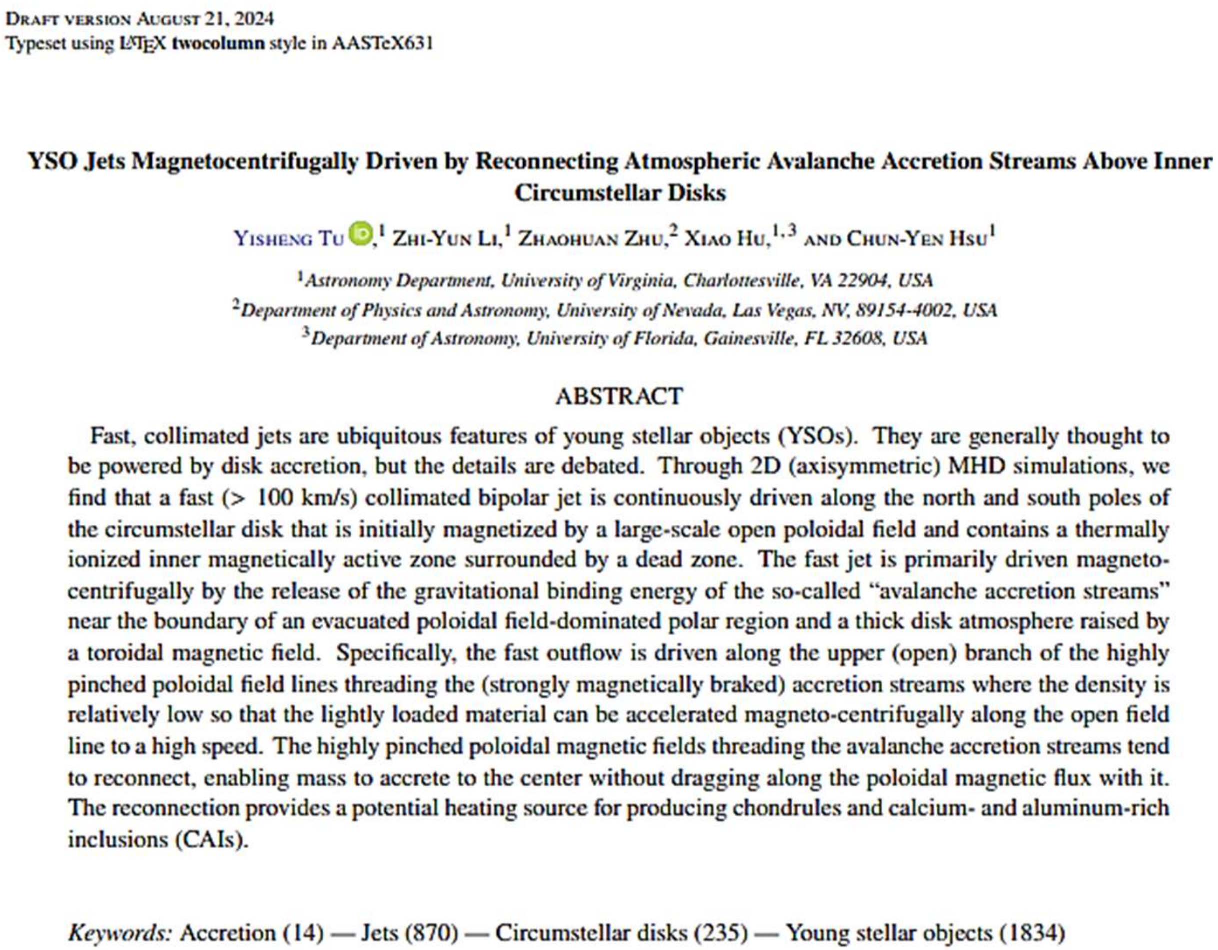
Draft version May 25, 2024

ABSTRACT

Partially-ionized plasmas consist of charged and neutral particles whose mutual collisions modify magnetic reconnection compared with the fully-ionized case. The collisions alter the rate and locations of the magnetic dissipation heating and the distribution of energies among the particles accelerated into the non-thermal tail. We examine the collisional regimes for the onset of fast reconnection in two environments: the partially-ionized layers of the solar atmosphere and the protoplanetary disks that are the birthplaces for planets around young stars. In both these environments, magnetic nulls readily develop into resistive current sheets in the regime where the charged and neutral particles are fully coupled by collisions, but the current sheets quickly break down under the ideal tearing instability. The current sheets collapse repeatedly, forming magnetic islands at successively smaller scales, till they enter a collisionally-decoupled regime where the magnetic energy is rapidly turned into heat and charged-particle kinetic energy. Small-scale, decoupled fast reconnection in the solar atmosphere may lead to preferential heating and energization of ions and electrons that escape into the corona. In protoplanetary disks such reconnection causes localized heating in the atmospheric layers that produce much of the infrared atomic and molecular line emission observed with the Spitzer and James Webb Space Telescopes.



Draft version August 21, 2024
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YSO Jets Magnetocentrifugally Driven by Reconnecting Atmospheric Avalanche Accretion Streams Above Inner Circumstellar Disks

Yisheng Tu,[1] Zhi-Yun Li,[1] Zhaohuan Zhu,[2] Xiao Hu,[1,3] and Chun-Yen Hsu[1]

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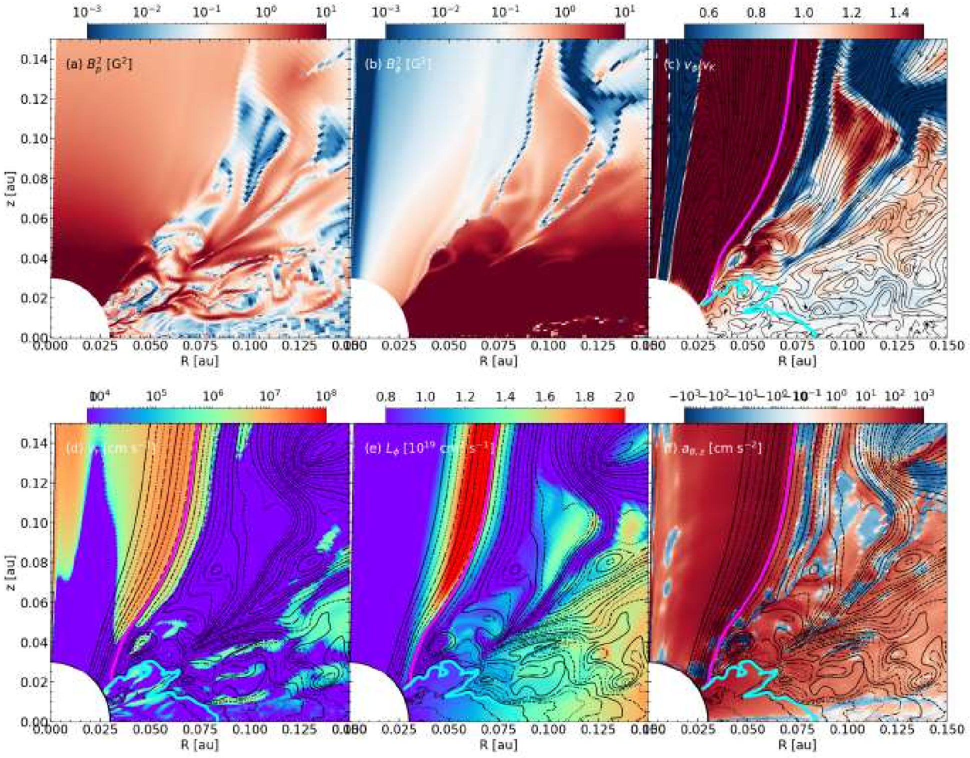
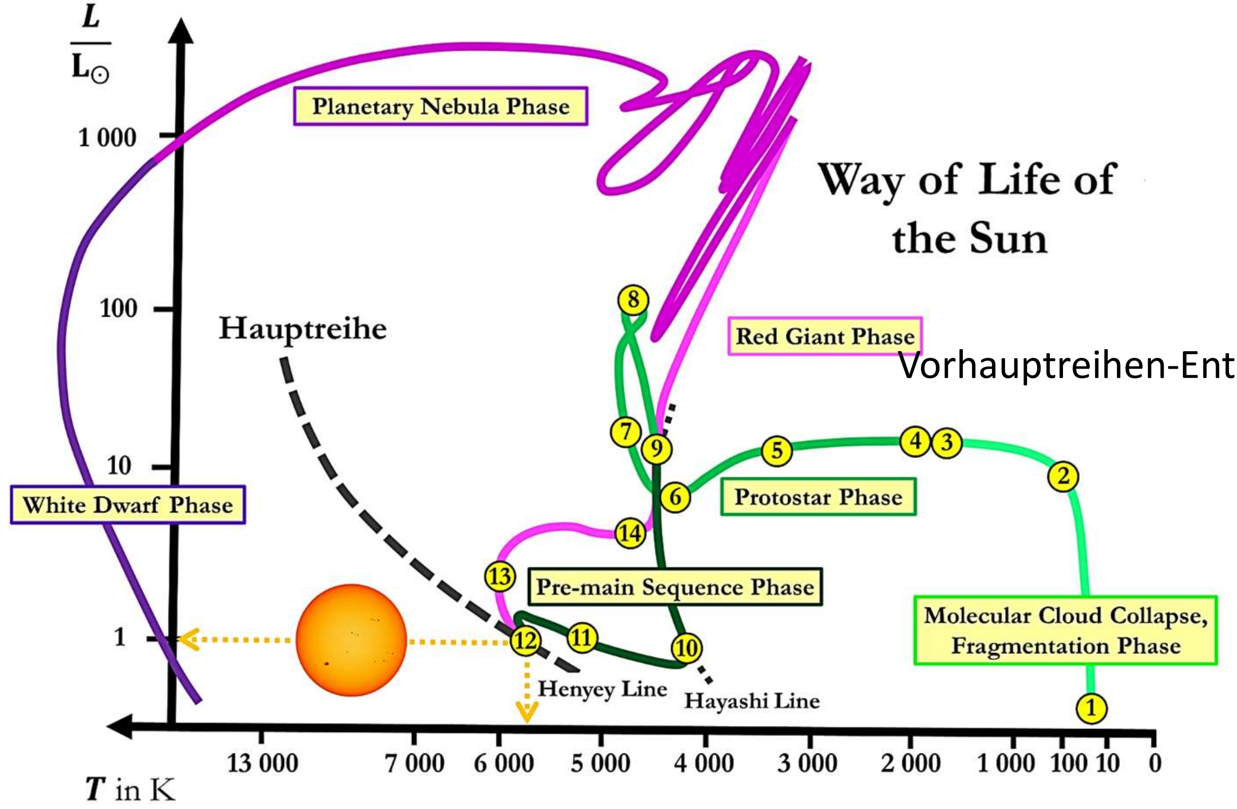
ABSTRACT

Fast, collimated jets are ubiquitous features of young stellar objects (YSOs). They are generally thought to be powered by disk accretion, but the details are debated. Through 2D (axisymmetric) MHD simulations, we find that a fast (> 100 km/s) collimated bipolar jet is continuously driven along the north and south poles of the circumstellar disk that is initially magnetized by a large-scale open poloidal field and contains a thermally ionized inner magnetically active zone surrounded by a dead zone. The fast jet is primarily driven magneto-centrifugally by the release of the gravitational binding energy of the so-called "avalanche accretion streams" near the boundary of an evacuated poloidal field-dominated polar region and a thick disk atmosphere raised by a toroidal magnetic field. Specifically, the fast outflow is driven along the upper (open) branch of the highly pinched poloidal field lines threading the (strongly magnetically braked) accretion streams where the density is relatively low so that the lightly loaded material can be accelerated magneto-centrifugally along the open field line to a high speed. The highly pinched poloidal magnetic fields threading the avalanche accretion streams tend to reconnect, enabling mass to accrete to the center without dragging along the poloidal magnetic flux with it. The reconnection provides a potential heating source for producing chondrules and calcium- and aluminum-rich inclusions (CAIs).

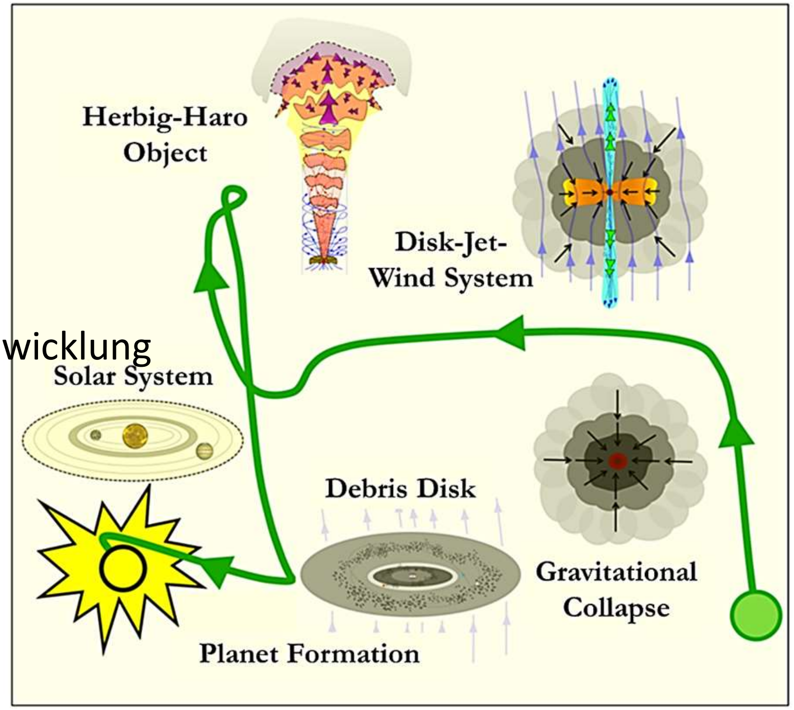
Keywords: Accretion (14) — Jets (870) — Circumstellar disks (235) — Young stellar objects (1834)





Way of Life of the Sun

Vorhauptreihen-Entwicklung



Pre-main Sequence Evolution

Molecular Cloud Collapse, Fragmentation Phase

① Compression and Fragmentation of the Gas Cloud, Formation of Bok Globules

② Termination of Isothermal collapse, Formation Quasi-hydrostatic Core, Adiabatic Increase in Central Temperature

③ Dissociation of Hydrogen Molecules, Core Collapse, Formation of Protostar, Onset of Ionization

Developments in the Protostar Phase

④ Protostellar Disk Formation, Onset of Deuterium Burning

⑤ Dynamo Generated Magnetic Fields, Sunspots, Prominences, Flares, Solar Wind

⑥ Obstruction of Matter Accretion by Solar Wind

⑦ Akkretionshülle zunehmend durchsichtiger

⑧ Transition from Dust to Gas Photosphere

Developments in the Pre-main Sequence Phase

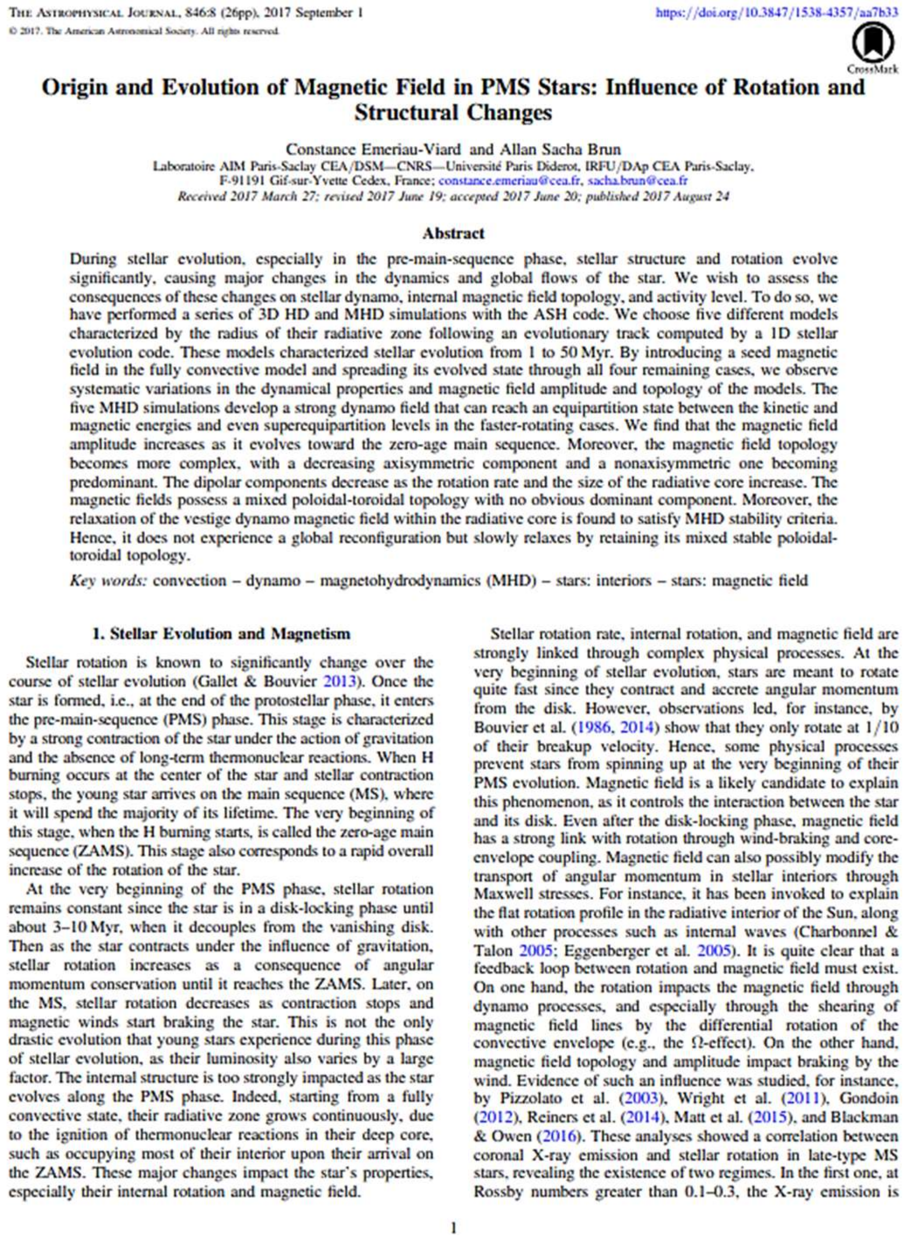
⑨ Crossing the Birthline, Hydrostatic Contraction of the almost Fully Convective Star along the Hayashi Line

⑩ Beginning of Central Radiative Transport, Development along Henyey Line

⑪ Beginning of Hydrogen Nuclear Fusion

⑫ Reaching the Main Sequence

U. v. Kusserow



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Origin and Evolution of Magnetic Field in PMS Stars: Influence of Rotation and Structural Changes

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Abstract

During stellar evolution, especially in the pre-main-sequence phase, stellar structure and rotation evolve significantly, causing major changes in the dynamics and global flows of the star. We wish to assess the consequences of these changes on stellar dynamo, internal magnetic field topology, and activity level. To do so, we have performed a series of 3D HD and MHD simulations with the ASH code. We choose five different models characterized by the radius of their radiative zone following an evolutionary track computed by a 1D stellar evolution code. These models characterized stellar evolution from 1 to 50 Myr. By introducing a seed magnetic field in the fully convective model and spreading its evolved state through all four remaining cases, we observe systematic variations in the dynamical properties and magnetic field amplitude and topology of the models. The five MHD simulations develop a strong dynamo field that can reach an equipartition state between the kinetic and magnetic energies and even superequipartition levels in the faster-rotating cases. We find that the magnetic field amplitude increases as it evolves toward the zero-age main sequence. Moreover, the magnetic field topology becomes more complex, with a decreasing axisymmetric component and a nonaxisymmetric one becoming predominant. The dipolar components decrease as the rotation rate and the size of the radiative core increase. The magnetic fields possess a mixed poloidal-toroidal topology with no obvious dominant component. Moreover, the relaxation of the vestige dynamo magnetic field within the radiative core is found to satisfy MHD stability criteria. Hence, it does not experience a global reconfiguration but slowly relaxes by retaining its mixed stable poloidal-toroidal topology.

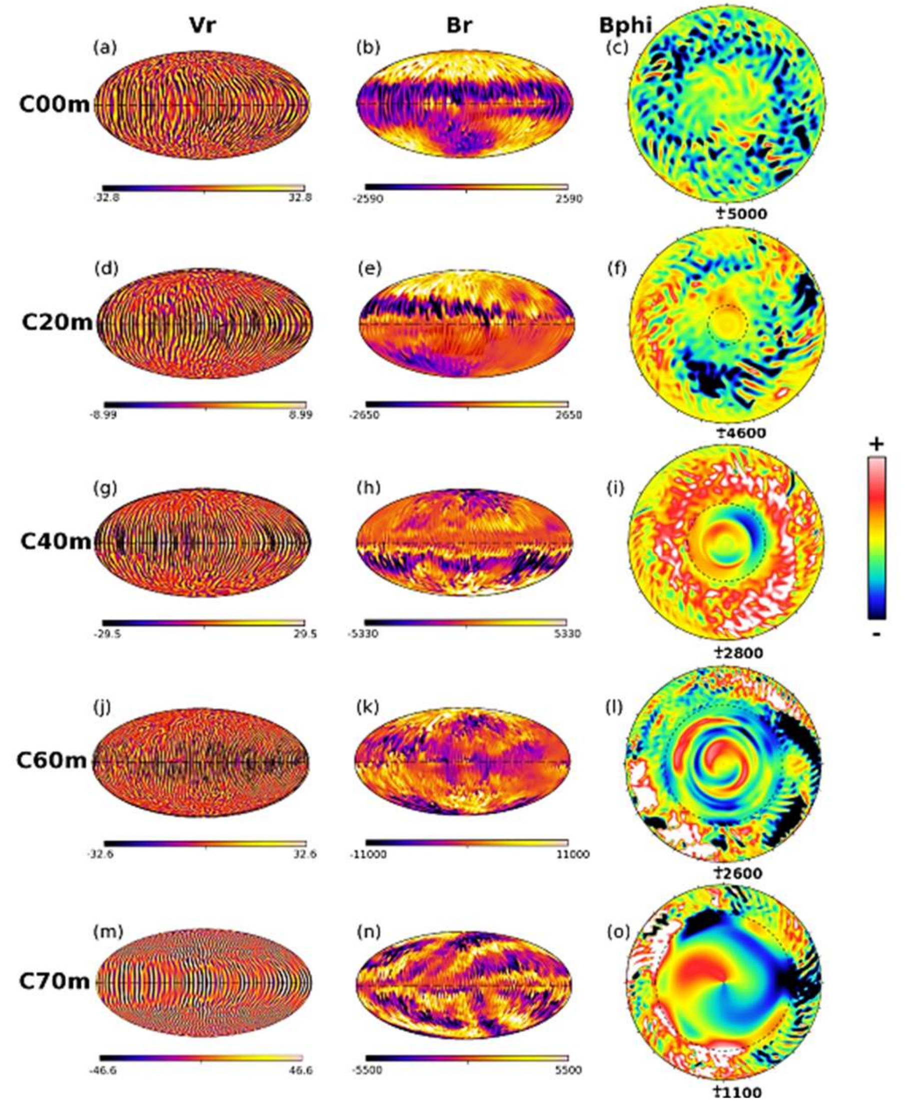
Key words: convection – dynamo – magnetohydrodynamics (MHD) – stars: interiors – stars: magnetic field

1. Stellar Evolution and Magnetism

Stellar rotation is known to significantly change over the course of stellar evolution (Gallet & Bouvier 2013). Once the star is formed, i.e., at the end of the protostellar phase, it enters the pre-main-sequence (PMS) phase. This stage is characterized by a strong contraction of the star under the action of gravitation and the absence of long-term thermonuclear reactions. When H burning occurs at the center of the star and stellar contraction stops, the young star arrives on the main sequence (MS), where it will spend the majority of its lifetime. The very beginning of this stage, when the H burning starts, is called the zero-age main sequence (ZAMS). This stage also corresponds to a rapid overall increase of the rotation of the star.

At the very beginning of the PMS phase, stellar rotation remains constant since the star is in a disk-locking phase until about 3–10 Myr, when it decouples from the vanishing disk. Then as the star contracts under the influence of gravitation, stellar rotation increases as a consequence of angular momentum conservation until it reaches the ZAMS. Later, on the MS, stellar rotation decreases as contraction stops and magnetic winds start braking the star. This is not the only drastic evolution that young stars experience during this phase of stellar evolution, as their luminosity also varies by a large factor. The internal structure is too strongly impacted as the star evolves along the PMS phase. Indeed, starting from a fully convective state, their radiative zone grows continuously, due to the ignition of thermonuclear reactions in their deep core, such as occupying most of their interior upon their arrival on the ZAMS. These major changes impact the star's properties, especially their internal rotation and magnetic field.

Stellar rotation rate, internal rotation, and magnetic field are strongly linked through complex physical processes. At the very beginning of stellar evolution, stars are meant to rotate quite fast since they contract and accrete angular momentum from the disk. However, observations led, for instance, by Bouvier et al. (1986, 2014) show that they only rotate at 1/10 of their breakup velocity. Hence, some physical processes prevent stars from spinning up at the very beginning of their PMS evolution. Magnetic field is a likely candidate to explain this phenomenon, as it controls the interaction between the star and its disk. Even after the disk-locking phase, magnetic field has a strong link with rotation through wind-braking and core-envelope coupling. Magnetic field can also possibly modify the transport of angular momentum in stellar interiors through Maxwell stresses. For instance, it has been invoked to explain the flat rotation profile in the radiative interior of the Sun, along with other processes such as internal waves (Charbonnel & Talon 2005; Eggenberger et al. 2005). It is quite clear that a feedback loop between rotation and magnetic field must exist. On one hand, the rotation impacts the magnetic field through dynamo processes, and especially through the shearing of magnetic field lines by the differential rotation of the convective envelope (e.g., the Ω-effect). On the other hand, magnetic field topology and amplitude impact braking by the wind. Evidence of such an influence was studied, for instance, by Pizzolato et al. (2003), Wright et al. (2011), Gondoin (2012), Reiners et al. (2014), Matt et al. (2015), and Blackman & Owen (2016). These analyses showed a correlation between coronal X-ray emission and stellar rotation in late-type MS stars, revealing the existence of two regimes. In the first one, at Rossby numbers greater than 0.1–0.3, the X-ray emission is



Left and middle columns : shell slices at the surface of **radial velocity** and **radial magnetic field** for the five MHD simulations. Right column: **equatorial** slice of $\boldsymbol{B_\varphi}$ for each model.

arXiv:2410.14777v1 [astro-ph.SR] 18 Oct 2024

The High-resolution Accretion Disks of Embedded protoStars (HADES) simulations. I. Impact of Protostellar Magnetic Fields on the Accretion Modes

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

How embedded, actively accreting low-mass protostars accrete their mass is still greatly debated. Observations are now piecing together the puzzle of embedded protostellar accretion, in particular with new facilities in the near-infrared. However, high-resolution theoretical models are still lacking, with a stark paucity of detailed simulations of these early phases. Here we present high-resolution non-ideal magneto-hydrodynamic simulations of a Solar mass protostar accreting at rates exceeding $10^{-6} M_\odot$ yr^{-1}. We show the results of the accretion flow for four different protostellar magnetic fields, 10 G, 500 G, 1 kG, and 2 kG, combined with a disk magnetic field. For weaker (10 G and 500 G) protostar magnetic fields, accretion occurs via a turbulent boundary layer mode, with disk material impacting across the protostellar surface. In the 500 G model, the presence of a magnetically dominated outflow focuses the accretion towards the equator, slightly enhancing and ordering the accretion. For kG magnetic fields, the disk becomes truncated due to the protostellar dipole and exhibits magnetospheric accretion, with the 2 kG model having accretion bursts induced by the interchange instability. We present bolometric light curves for the models and find that they reproduce observations of Class I protostars from YSOVAR, with high bursts followed by an exponential decay possibly being a signature of instability-driven accretion. Finally, we present the filling fractions of accretion and find that 90% of the mass is accreted in a surface area fraction of 10-20%. These simulations will be extended in future work for a broader parameter space, with their high resolution and high temporal spacing able to explore a wide range of interesting protostellar physics.

Key words. Stars: protostars – Accretion, accretion disks – Methods: numerical

1. Introduction

Protostars are the bloated embryos of main-sequence stars that are actively accreting material from their natal environments. In the earlier phases of evolution, low-mass protostars are still deeply embedded within their natal cores and surrounded by relatively massive disks, resulting in substantial accretion rates, $\dot{m}_* \geq 10^{-7} M_\odot$ yr^{-1}. Direct knowledge of how protostars accrete their mass typically comes from observations at more evolved stages, such as T-Tauri stars, when the central protostar is exposed, the disks have been largely depleted and the accretion rates drop below $\dot{m}_* \leq 10^{-8} M_\odot$ yr^{-1}. Since these objects are exposed, it becomes significantly more feasible to observe emission from the accretion zones, primarily in the form of X-rays (Feigelson & Montmerle 1999; Feigelson et al. 2007), ultraviolet emission (Manara et al. 2023) and hydrogen recombination emission (Fischer et al. 2023). There are indirect methods to estimate the accretion rate, such as determining the properties of protostellar outflows and inferring the accretion rate via theoretical models (e.g. Avison et al. 2021). Modern observational facilities, such as the Very Large Telescope Interferometer (VLTI) with the GRAVITY instrument, are now probing the accretion of more embedded systems, tracing evolutionary times when most of the protostar's mass has already been accumulated (e.g., Gravity Collaboration et al. 2023b,a). During the main accretion phases of protostar formation, the protostar's natal core and disk obscure the accretion zone, complicating efforts to directly probe the inner accretion disks and follow how the material is delivered onto the protostar.

Multi-physics star formation simulations can capture the earliest phases of star formation from the large scales (sub-parsec for core-scale simulations and 1-10s of parsec for molecular cloud simulations) (e.g. Dale et al. 2012; Rosen et al. 2016; Offner & Chaban 2017; Seifried et al. 2017; Cunningham et al. 2018; Wurster et al. 2019; Rosen & Krumholz 2020; Grudić et al. 2021; Rosen 2022; Suin et al. 2024), but must use subgrid prescriptions to model the protostar as an unmagnetized sink particle which accretes mass from an assumed accretion region (Offner et al. 2009; Bleuler & Teyssier 2014). These simulations are broadly able to reproduce the accretion rates from analytic accretion models (i.e. Shu 1977; Bonnell et al. 2001; McKee & Tan 2003). However, these parsec-scale simulations cannot resolve the accretion flow directly onto the protostar due to resolution constraints: resolving from molecular cloud scales to the protostellar surface requires spanning 7-8 orders of magnitude across length scales. The combined theoretical and observational challenges mean the underlying physical processes of protostel-

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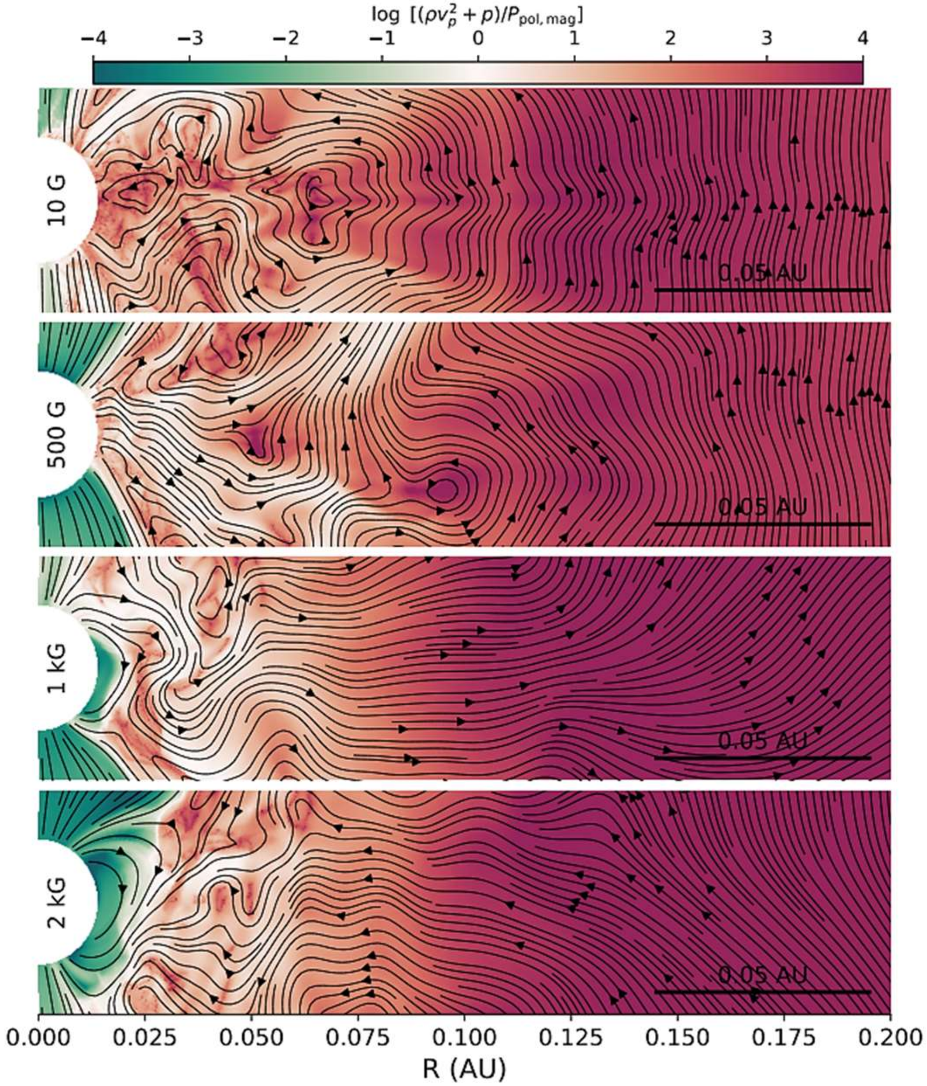
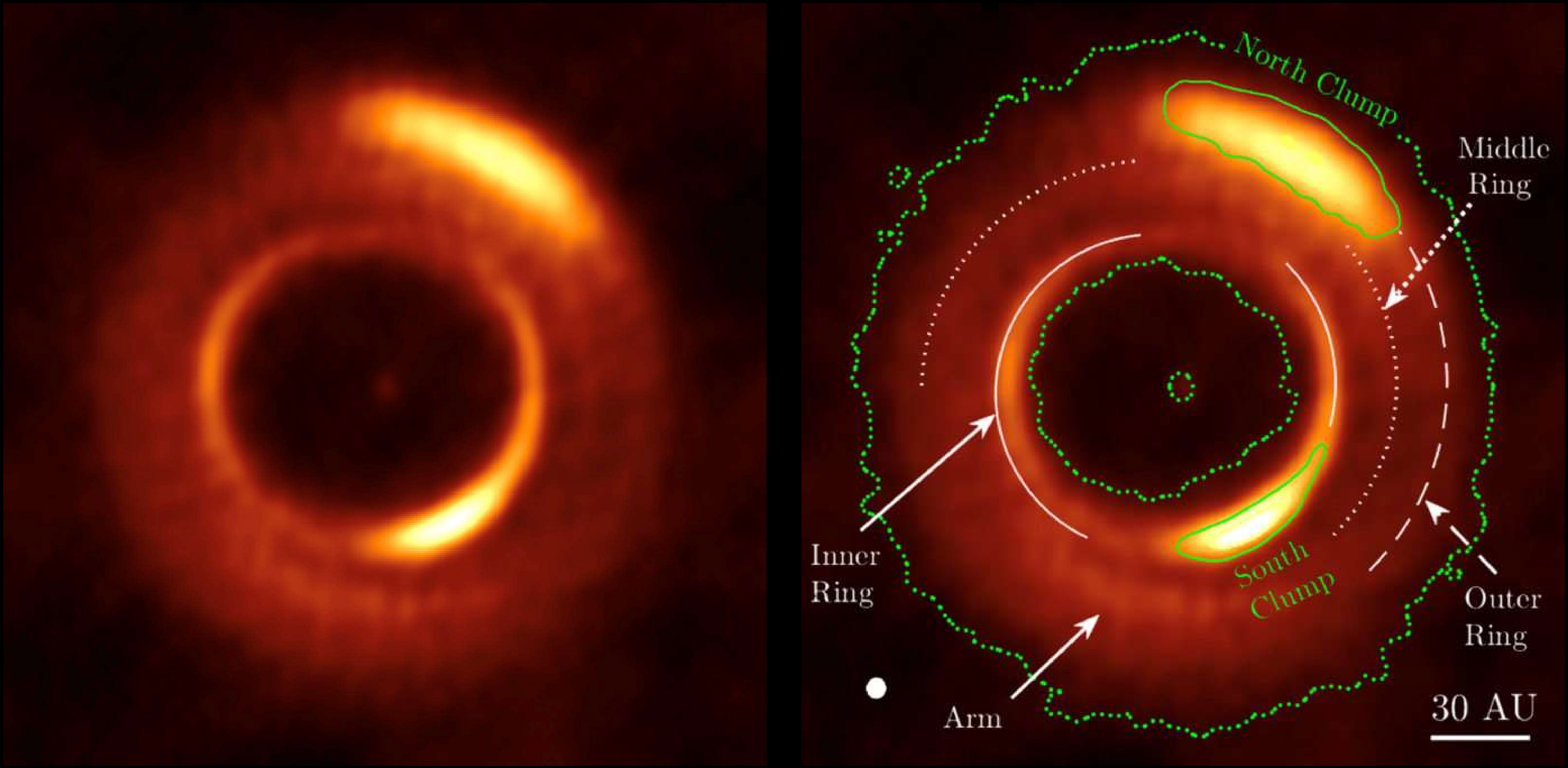


The ratio of the poloidal ram pressure plus thermal pressure to the poloidal magnetic pressure within the inner 0.2 AU of the disk

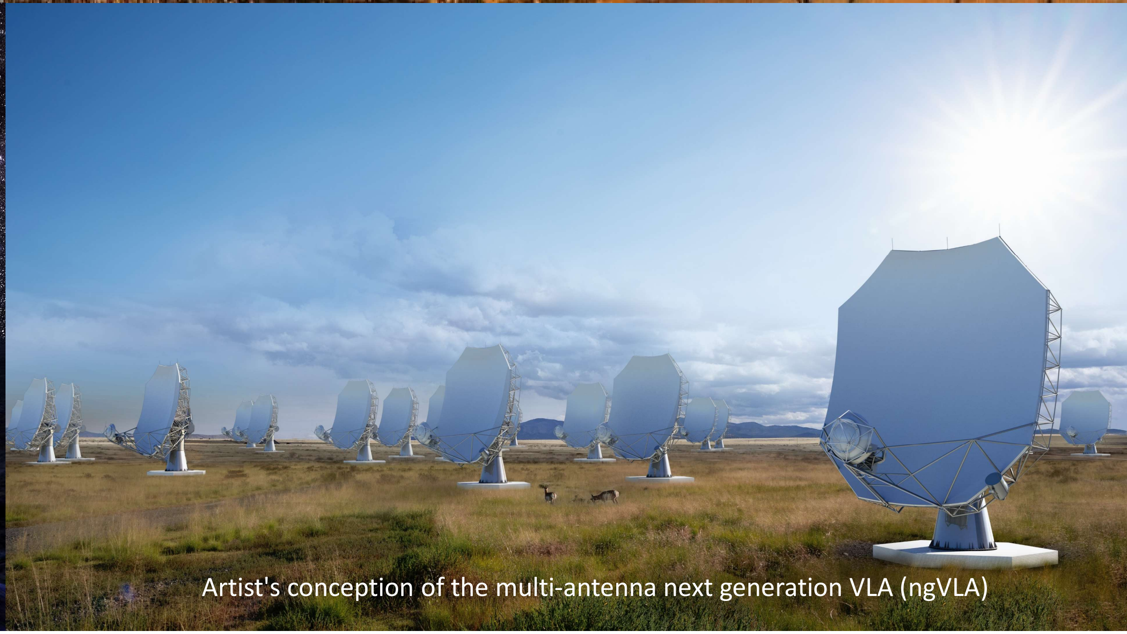

North Clump
Middle Ring
Inner Ring
South Clump
Outer Ring
Arm
30 AU

Exciting structures in a young Protoplanetary Disk that support Planet Formation - ALMA (ESO/NAOJ/NRAO)/Dong et al.

Artist's conception of the Extremely Large Telescope (ELT)

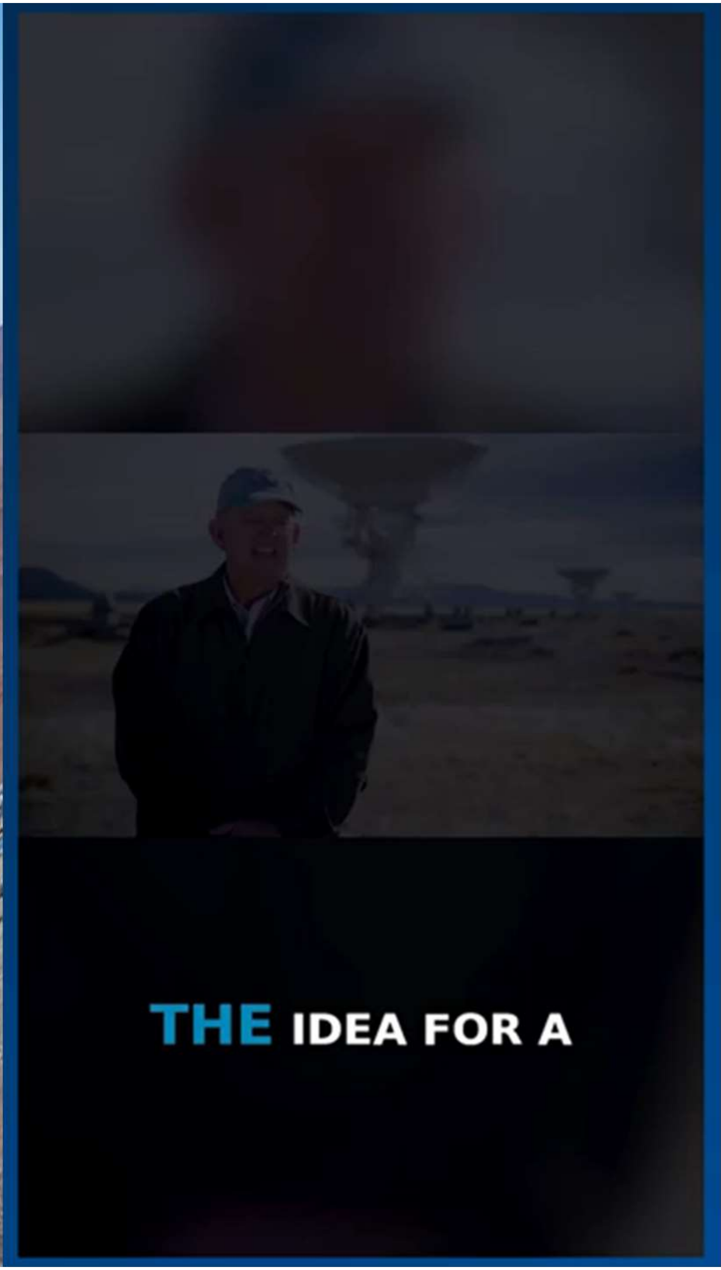
Artist´s conception Square Kilometre Array Observatory (SKAO)

Artist's conception of the Giant Magellan Telescope (GMT)



Artist's conception of the multi-antenna next generation VLA (ngVLA)

Shielding the Extremely Large Telescope from the Atacama Desert | ELT Updates - ESO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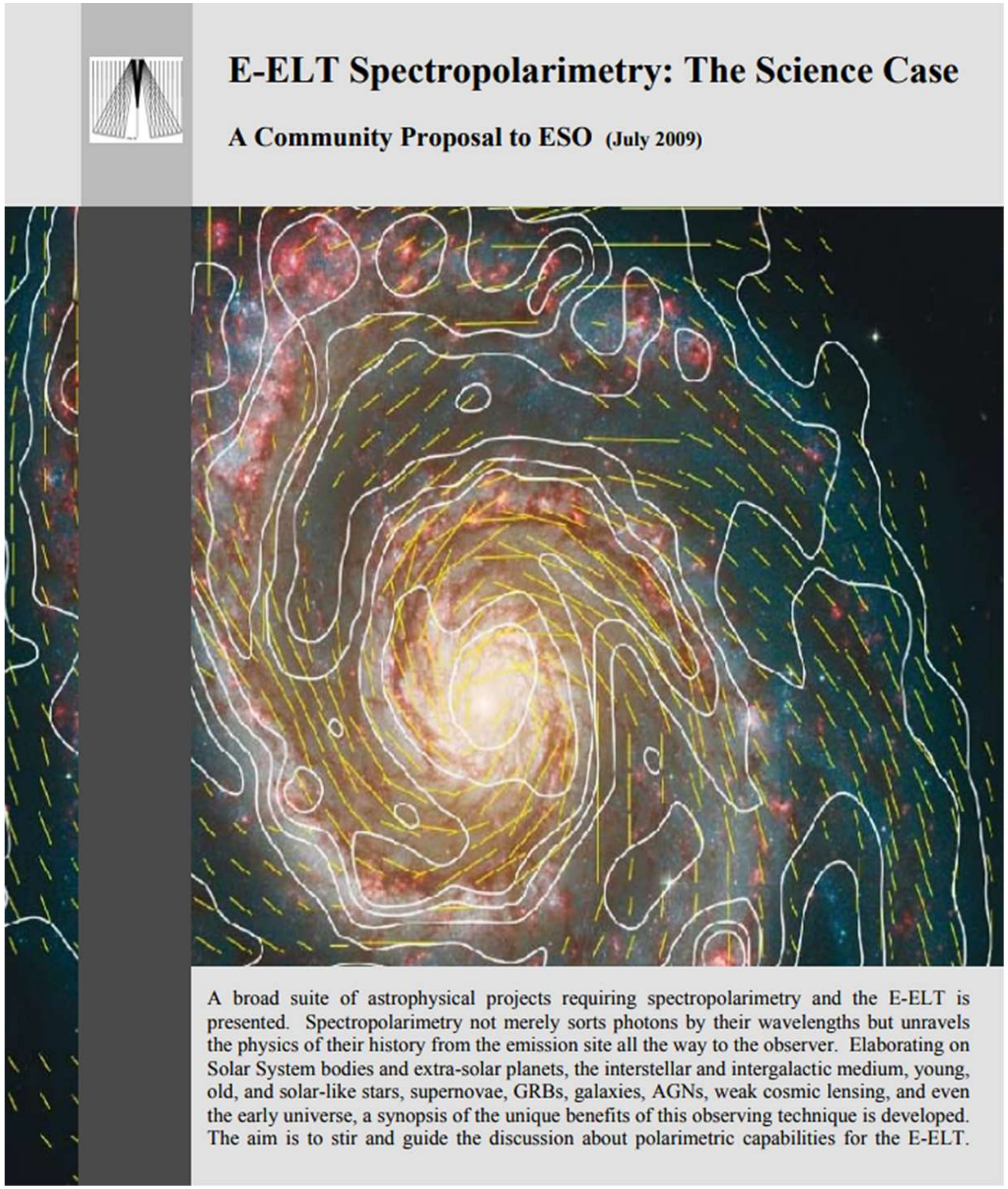
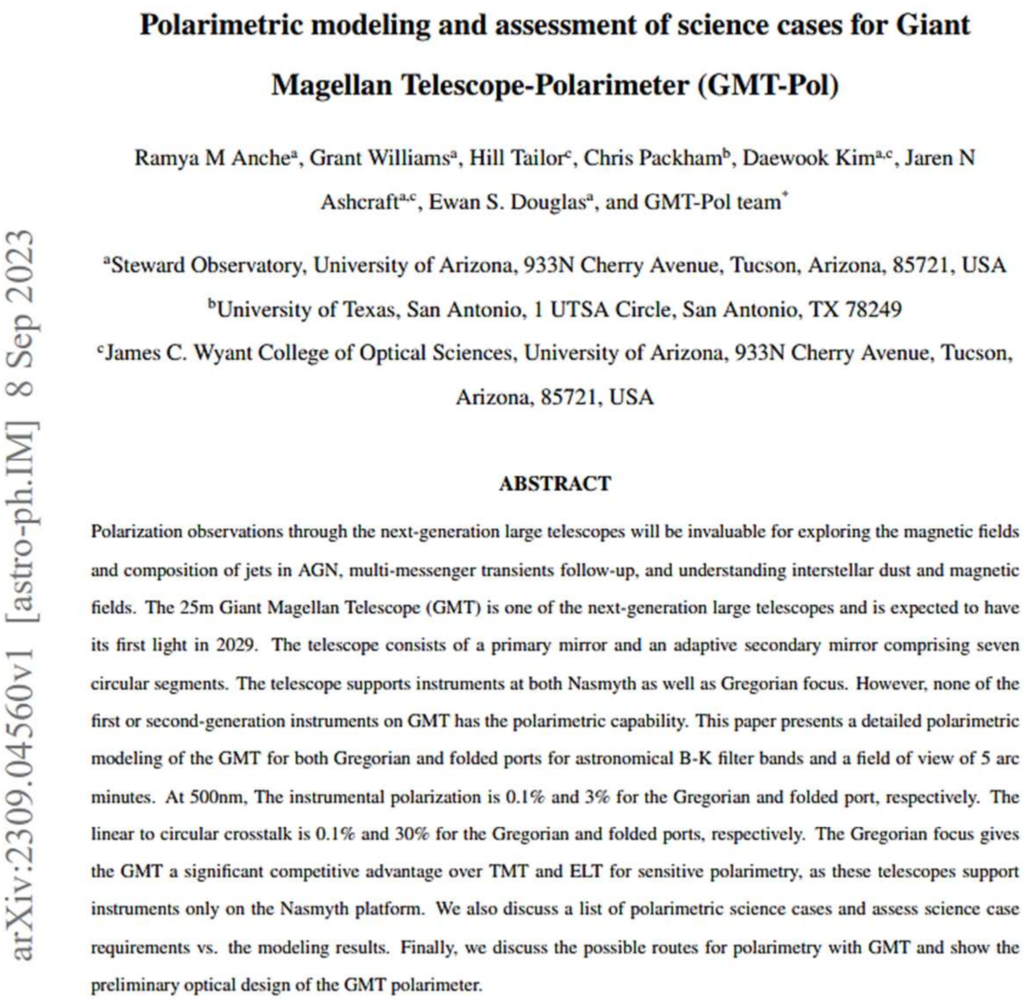


E-ELT Spectropolarimetry: The Science Case

A Community Proposal to ESO (July 2009)

A broad suite of astrophysical projects requiring spectropolarimetry and the E-ELT is presented. Spectropolarimetry not merely sorts photons by their wavelengths but unravels the physics of their history from the emission site all the way to the observer. Elaborating on Solar System bodies and extra-solar planets, the interstellar and intergalactic medium, young, old, and solar-like stars, supernovae, GRBs, galaxies, AGNs, weak cosmic lensing, and even the early universe, a synopsis of the unique benefits of this observing technique is developed. The aim is to stir and guide the discussion about polarimetric capabilities for the E-ELT.



arXiv:2309.04560v1 [astro-ph.IM] 8 Sep 2023

Polarimetric modeling and assessment of science cases for Giant Magellan Telescope-Polarimeter (GMT-Pol)

Ramya M Anche[a], Grant Williams[a], Hill Tailor[c], Chris Packham[b], Daewook Kim[a,c], Jaren N Ashcraft[a,c], Ewan S. Douglas[a], and GMT-Pol team[*]

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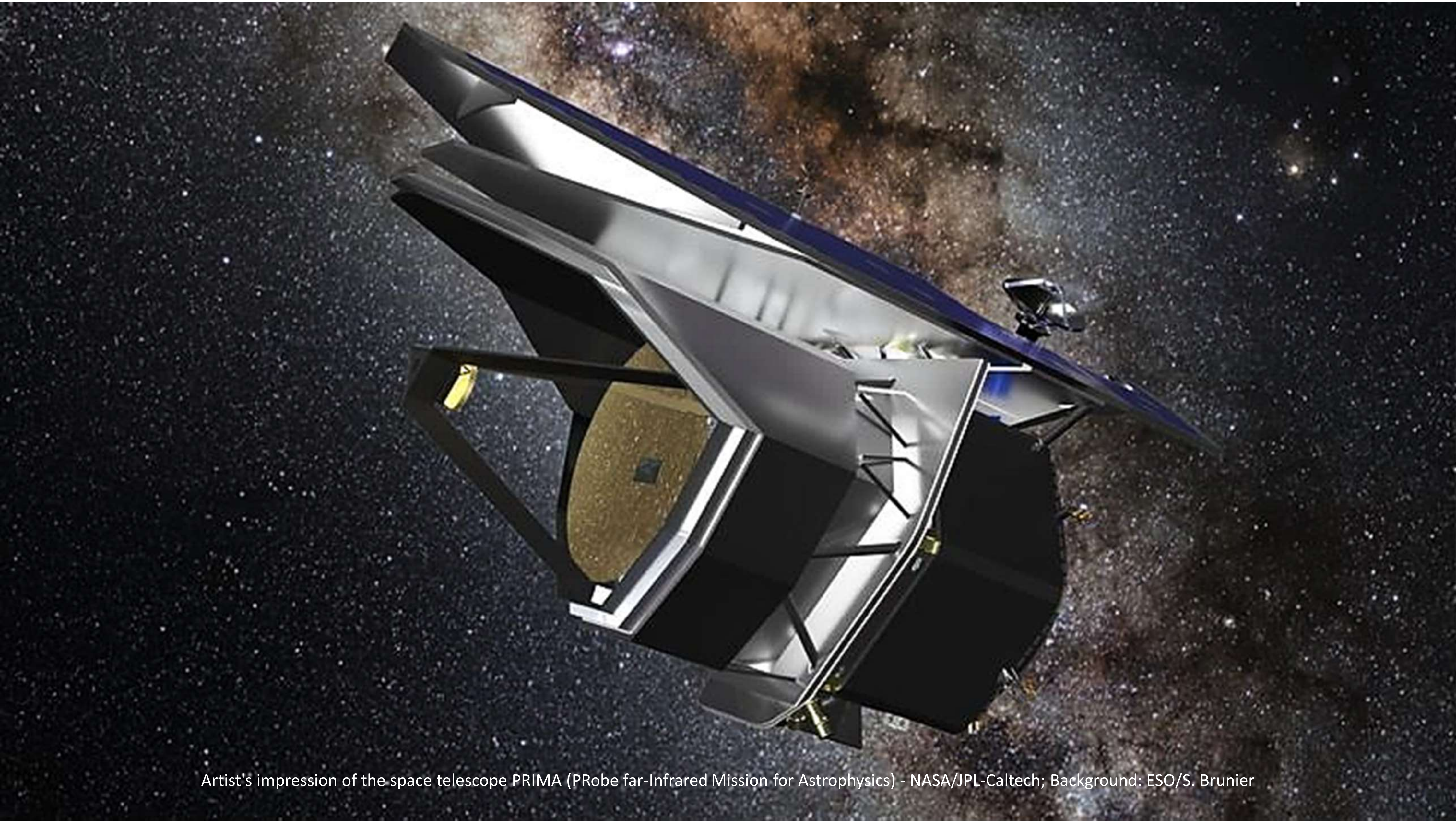
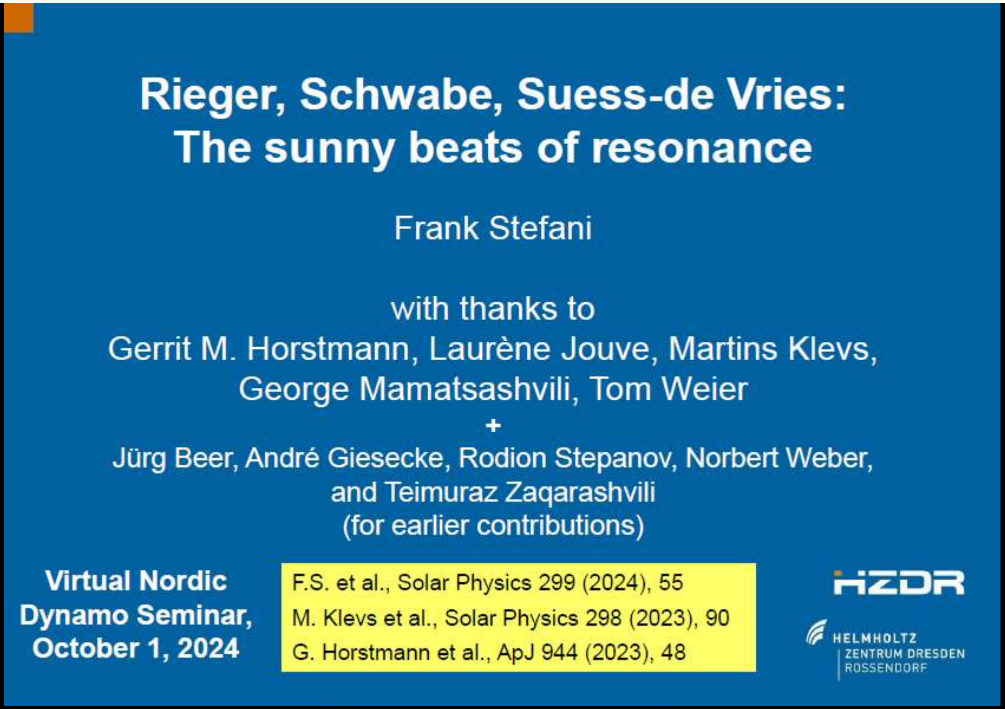
ABSTRACT

Polarization observations through the next-generation large telescopes will be invaluable for exploring the magnetic fields and composition of jets in AGN, multi-messenger transients follow-up, and understanding interstellar dust and magnetic fields. The 25m Giant Magellan Telescope (GMT) is one of the next-generation large telescopes and is expected to have its first light in 2029. The telescope consists of a primary mirror and an adaptive secondary mirror comprising seven circular segments. The telescope supports instruments at both Nasmyth as well as Gregorian focus. However, none of the first or second-generation instruments on GMT has the polarimetric capability. This paper presents a detailed polarimetric modeling of the GMT for both Gregorian and folded ports for astronomical B-K filter bands and a field of view of 5 arc minutes. At 500nm, The instrumental polarization is 0.1% and 3% for the Gregorian and folded port, respectively. The linear to circular crosstalk is 0.1% and 30% for the Gregorian and folded ports, respectively. The Gregorian focus gives the GMT a significant competitive advantage over TMT and ELT for sensitive polarimetry, as these telescopes support instruments only on the Nasmyth platform. We also discuss a list of polarimetric science cases and assess science case requirements vs. the modeling results. Finally, we discuss the possible routes for polarimetry with GMT and show the preliminary optical design of the GMT polarimeter.



Artist's impression of the space telescope PRIMA (PRobe far-Infrared Mission for Astrophysics) - NASA/JPL-Caltech; Background: ESO/S. Brunier



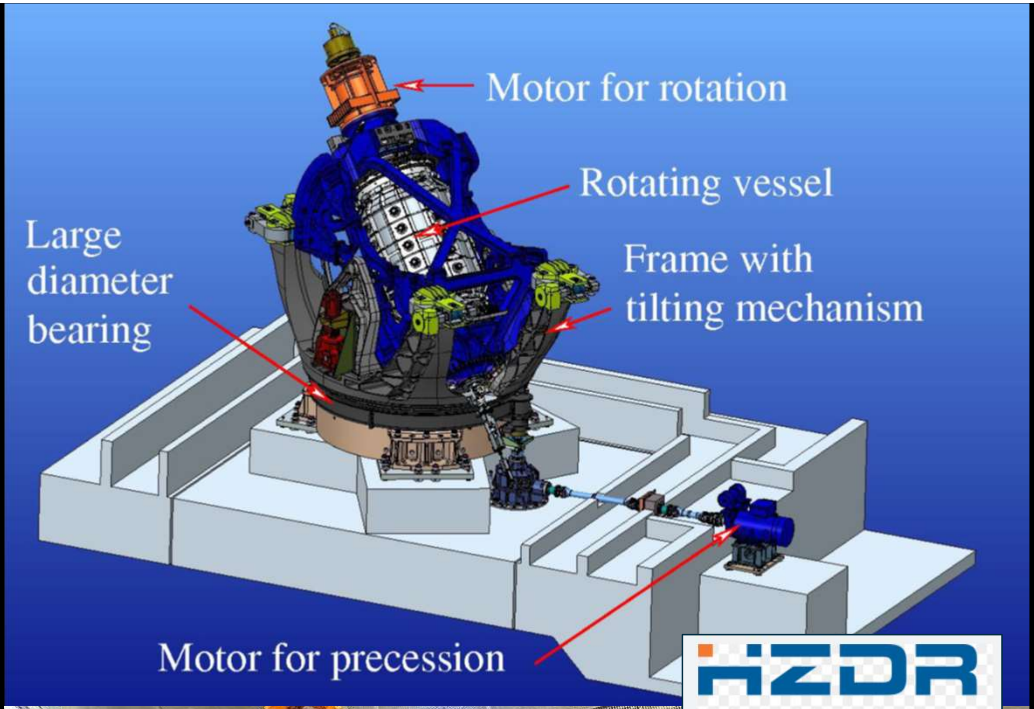
Rieger, Schwabe, Suess-de Vries: The sunny beats of resonance

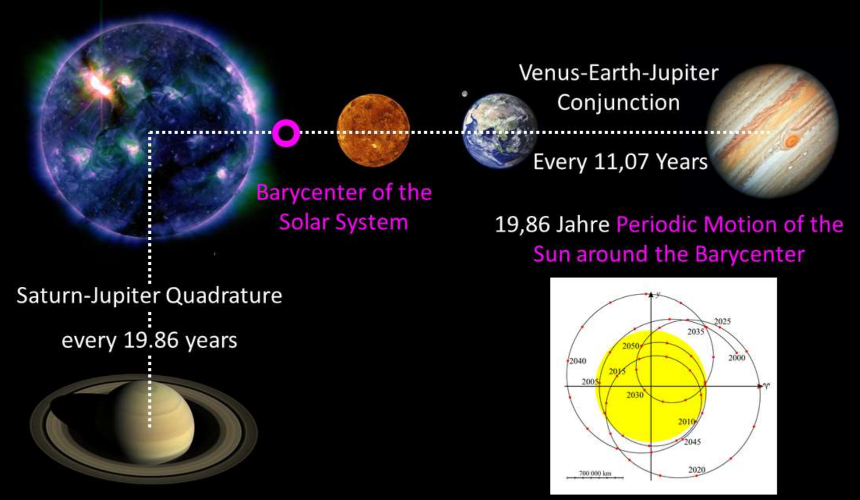
Frank Stefani

with thanks to
Gerrit M. Horstmann, Laurène Jouve, Martins Klevs,
George Mamatsashvili, Tom Weier
+
Jürg Beer, André Giesecke, Rodion Stepanov, Norbert Weber,
and Teimuraz Zaqarashvili
(for earlier contributions)

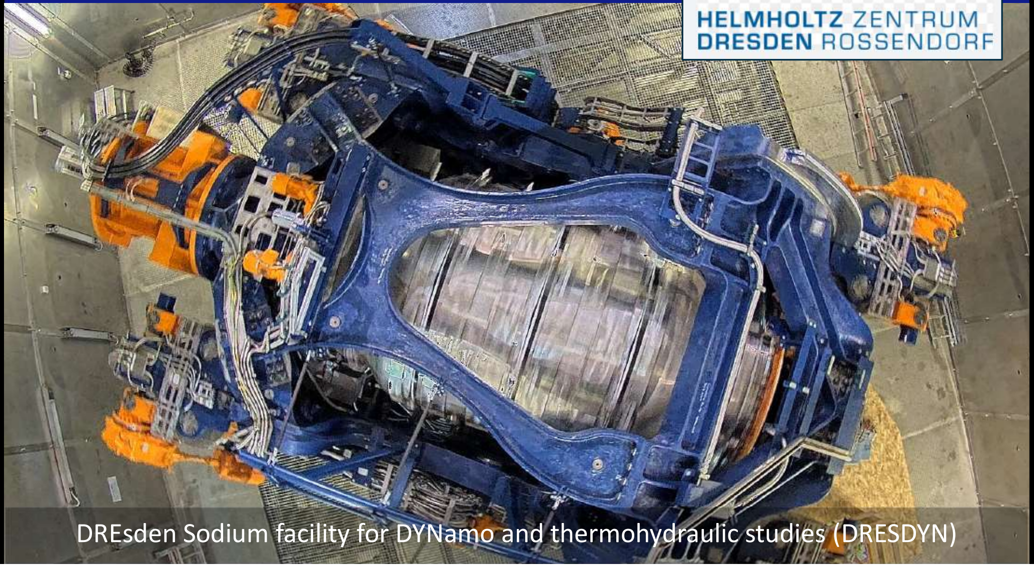
Virtual Nordic Dynamo Seminar, October 1, 2024

F.S. et al., Solar Physics 299 (2024), 55
M. Klevs et al., Solar Physics 298 (2023), 90
G. Horstmann et al., ApJ 944 (2023), 48


Motor for rotation
Rotating vessel
Large diameter bearing
Frame with tilting mechanism
Motor for precession


Venus-Earth-Jupiter Conjunction
Every 11,07 Years
Barycenter of the Solar System
19,86 Jahre Periodic Motion of the Sun around the Barycenter
Saturn-Jupiter Quadrature
every 19.86 years
2025
2035
2050
2000
2040
2015
2005
2030
2010
2045
2020
700 000 km

Special motion sequences in the Solar System - U. v. Kusserow, NASA



DREsden Sodium facility for DYNamo and thermohydraulic studies (DRESDYN)

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Academy of Sciences

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Ariel University,
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Professor
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PhD Senior
Astrophysicist
American University, DC

Astrophysicist
A.A. Shlyapnikov
(Ukraine)

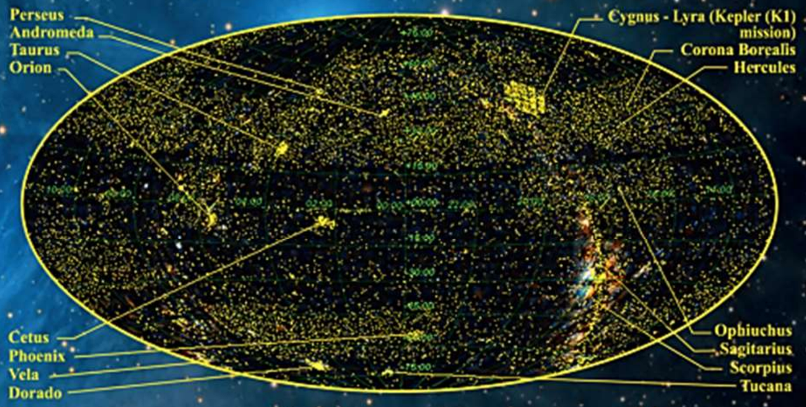
In the monograph, the authors systematize and generalize the results of studying solar-type activity that is characteristic of a significant part of mid- and low-mass stars of the Galaxy, outline the characteristics of such stars in the quiescent state, during the sporadic flares and variations of magnetic activity over the course of stellar evolution. The observational data taken over the whole range of the electromagnetic spectrum from decametric radio waves to X-rays are described in detail. The current models of stellar flares and stellar dynamo models are considered in two theoretical chapters. The last part of the book describes the impact of stellar activity of mid- and low-mass stars on exoplanetary environments. The Catalog of Stars with Solar-Type Activity is provided in the supplementary section.

The book is intended for researchers involved in studying the physics of stars and the Sun, graduate students, and students specialized in heliophysics, astrophysics, and in the field of space physics.

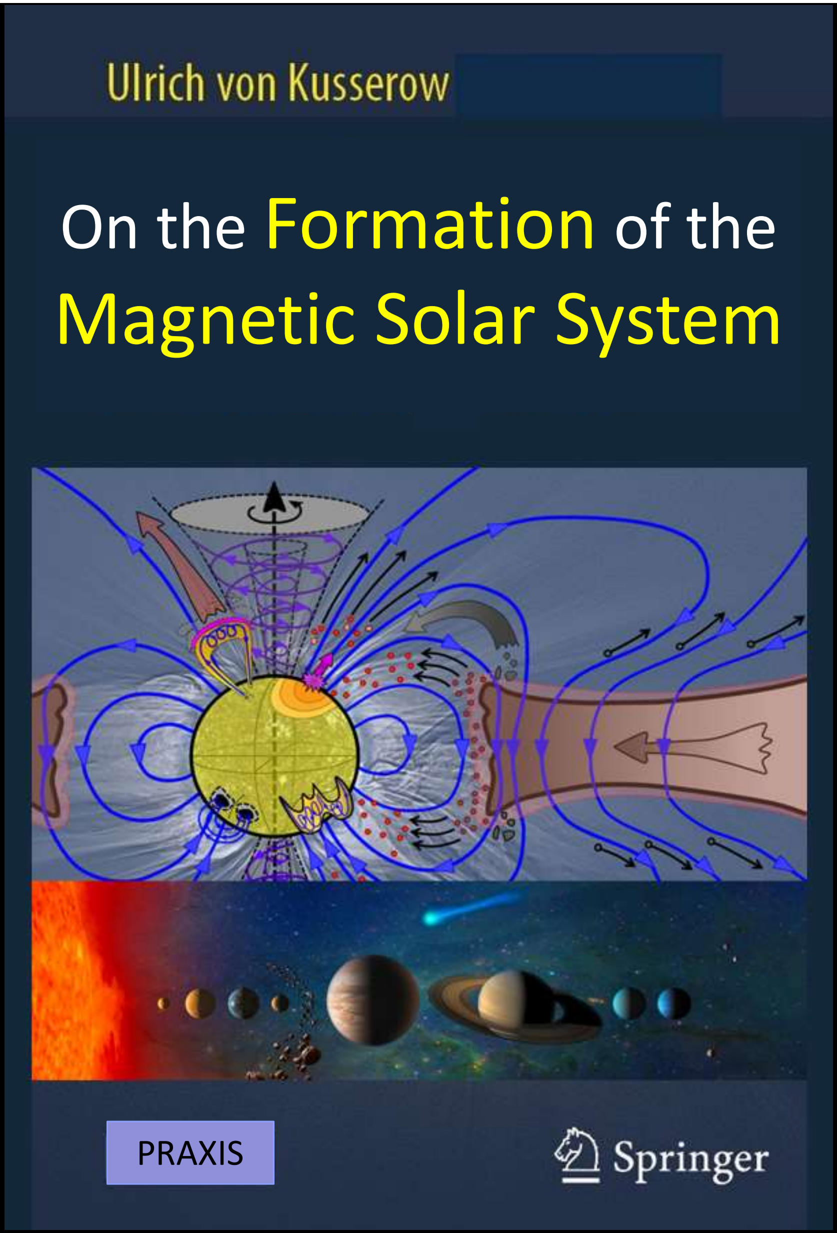
PHYSICS OF MID- AND LOW-MASS STARS WITH SOLAR-TYPE ACTIVITY
AND THEIR IMPACT ON EXOPLANETARY ENVIRONMENTS

R.E. Gershberg, N.I. Kleeorin,
L.A. Pustilnik, V.S. Airapetian,
A.A. Shlyapnikov

PHYSICS OF MID- AND LOW-MASS STARS WITH SOLAR-TYPE ACTIVITY AND THEIR IMPACT ON EXOPLANETARY ENVIRONMENTS



Distribution of 314618 stars with solar-type activity over the celestial sphere



Ulrich von Kusserow

On the Formation of the Magnetic Solar System

PRAXIS

Springer

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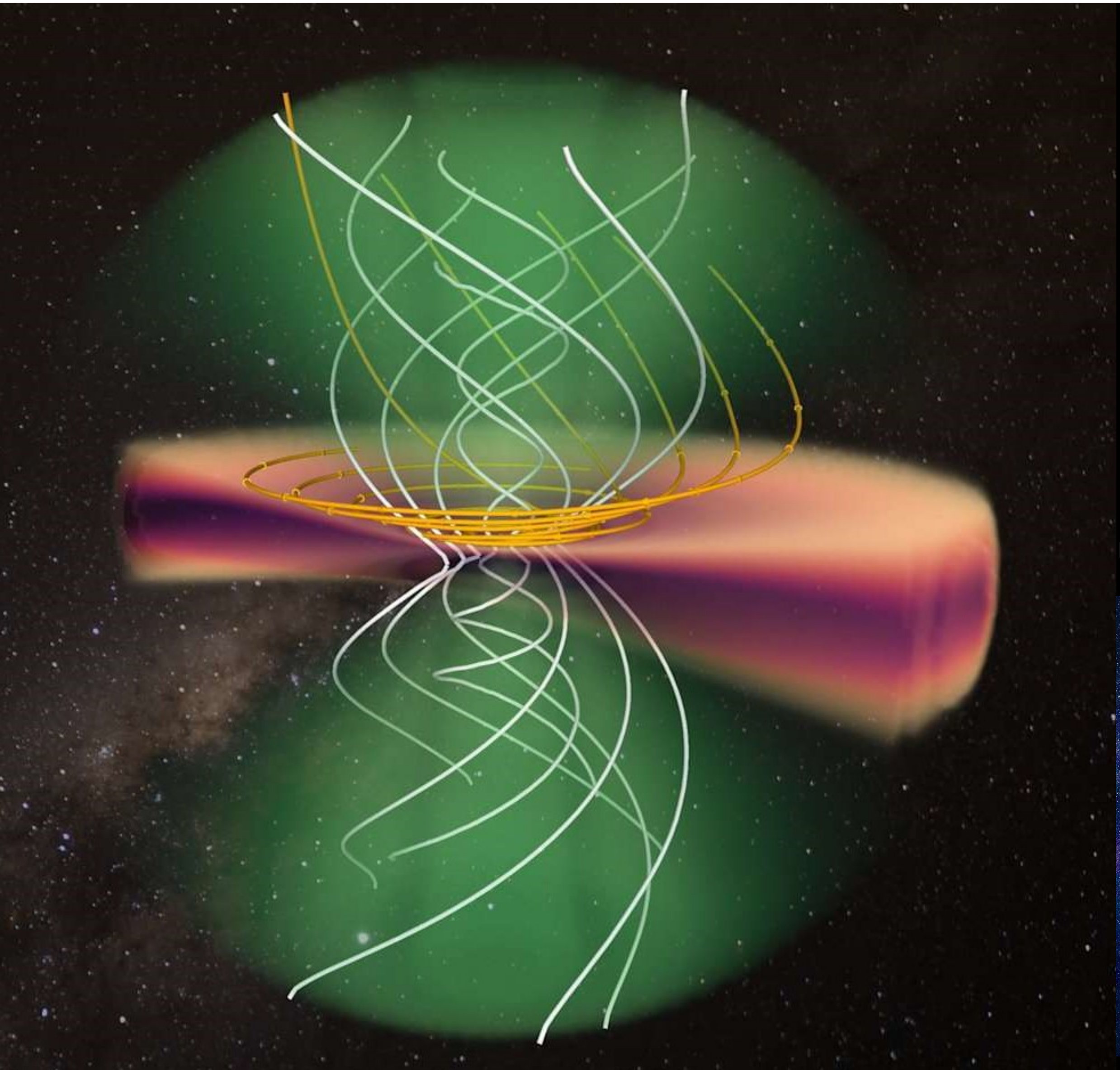
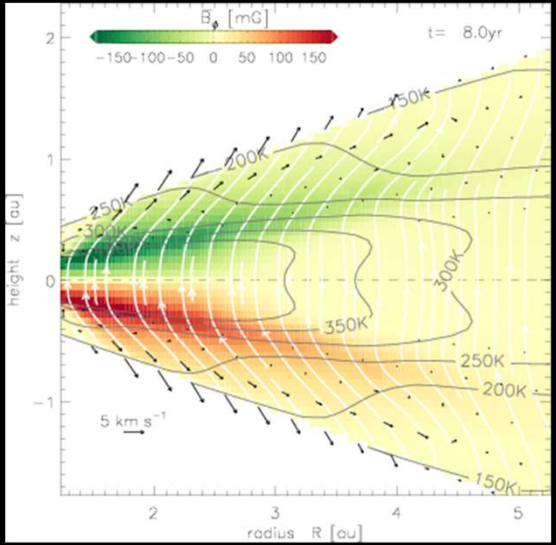
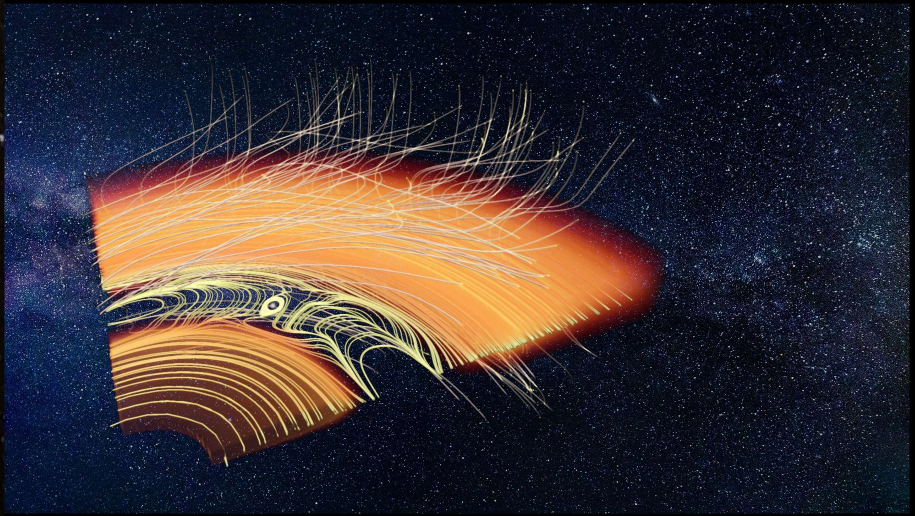


Simulation of a gas disk in a magnetized protostellar system
AIP/E. Sarafidou, O. Gressel; Background: AIP/A. Saviauk



MHD simulation of a protoplanetary disk with ambipolar diffusion - O. Gressel



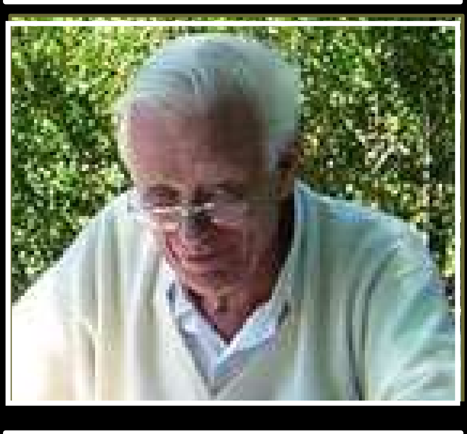
Simulated Planet Formation in a Magnetized Protoplanetary Disk - O. Gressel

„To **B** Or Not To **B** “

Virginia Trimble, 2001

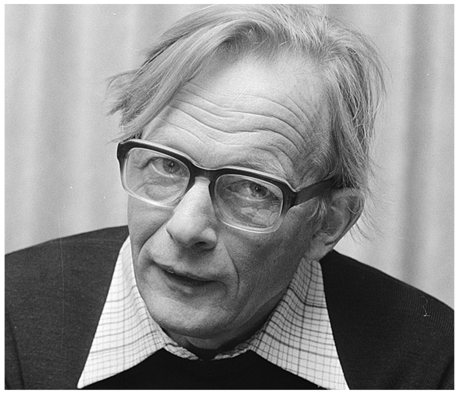
„The larger our ignorance, the stronger the magnetic field“

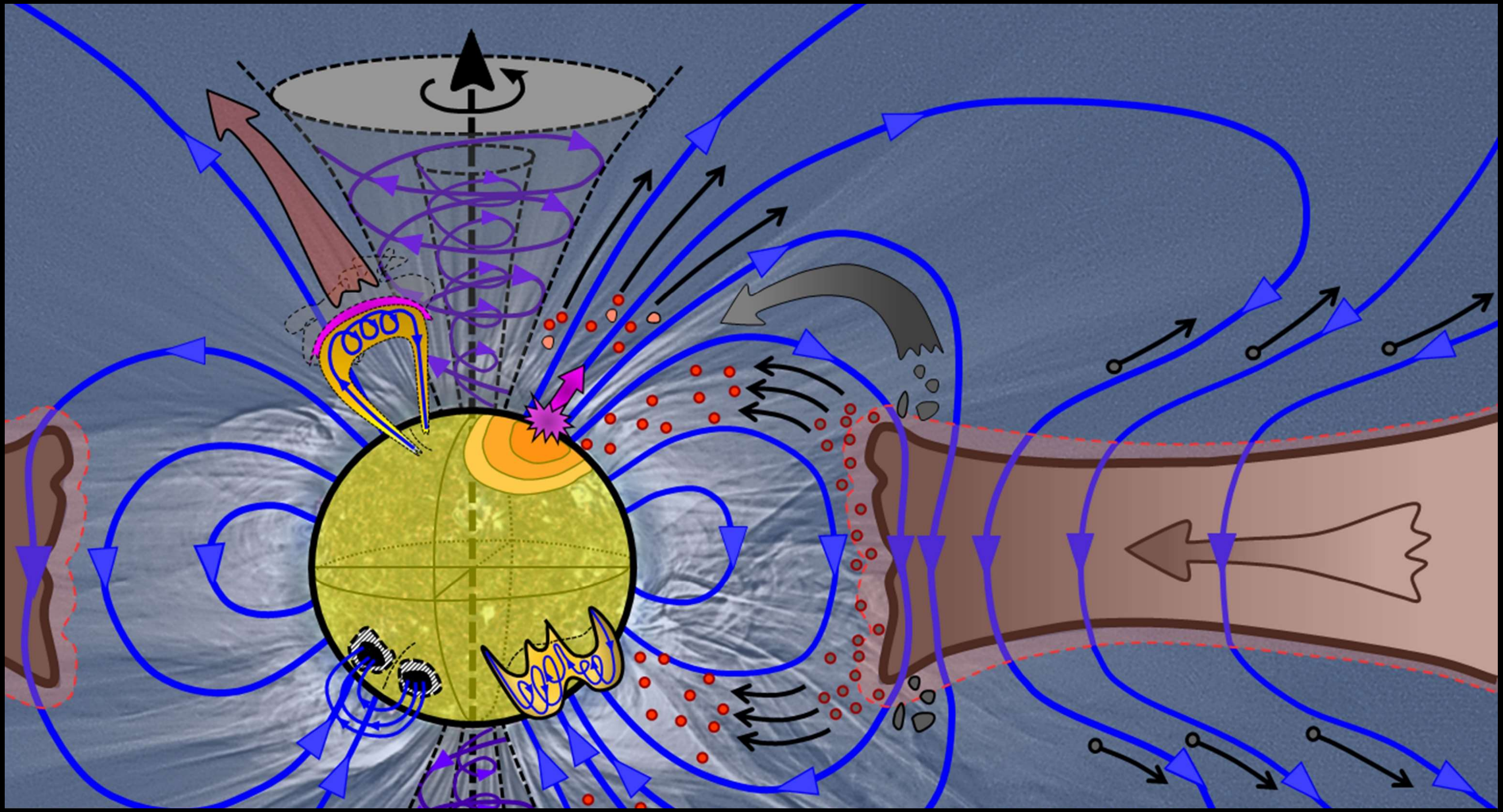
Lodewijk Woltjer, 1965



„Magnetic Fields are to Astrophysics as Sex is to Psychology“

Hendrik van der Hulst, 1987





$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{B}) - \vec{\nabla} \times (\eta_{\mathrm{OD}} \cdot \vec{\nabla} \times \vec{B}) + \vec{\nabla} \times \{\eta_{\mathrm{AD}} \cdot (\vec{\nabla} \times \vec{B}) \times \vec{B}\} - \vec{\nabla} \times [\vec{\nabla} \times \{\eta_{\mathrm{HD}} \cdot (\vec{\nabla} \times \vec{B}) \times \vec{B}\}]$$

U. v. Kusserow, Bremen

MHD and the Formation of the Magnetic Solar System

A didactically oriented approach