Observing Electric Currents in Space

Michael Clarage
Independent Researcher, Boston, MA, USA.
E-mail: michael.clarage@protonmail.com

To find evidence for electric currents in cosmic plasmas requires both that the currents be looked for, and that data be available to indicate their presence. This paper focuses on the second requirement, the available data, and how the flow of electric current in plasmas naturally will be difficult to observe from a distance. Coaxial current flow predicted and observed in plasmas is examined in some detail showing that even very large total current flows can give, when seen from a distance, very little signal. Examples are given from active galactic nuclei, planetary magnetospheres, and plasma ejections from moons. Suggestions are given for how to analyze existing astrophysical data and also for new measurements to be made that will show the presence of cosmic electric currents.

1 Introduction

In 1977, Hannes Alfven [1] wrote that at the galactic scale, electric currents of 10^{17}-10^{19} amperes would be natural. Forty years later measured estimates are of 10^{18} amperes in jets from active galactic nuclei [2, 3]. The accuracy of the 1977 prediction, so far in advance of observation, is a strong testament to Alfven and his colleagues, and an indication that more attention should be given to their work.

Kristian Birkeland is often credited with first describing cosmic electric currents in his 1908 model of electric currents flowing from the Sun to the Earth causing the aurora borealis [4]. For 60 years, Birkeland's theory of large-scale electrical connection was ignored in favor of the mathematical models of Sydney Chapman, where planets are electrically insulated from the Sun and solar wind.

The first in-situ measurements of cosmic-scaled electric currents were provided by Zmuda *et al* [5] with a single axis magnetometer on board the navigation satellite 1963–1938C. Today the presence of cosmic electric currents is acknowledged, but the debate remains if the electric fields and currents can be causal, or are merely a consequence of thermodynamic and ponderomotive processes.

Electric current flow in a coaxial configuration was first described in Oliver Heaviside's 1880 patent [6]. Attempted telegraph cables that sent current in only one direction required more energy and incurred substantial information loss compared to cables with a built-in design to accommodate a return current.

Coaxial current flow, now commonplace to the electrical engineer, is a new idea to many in the astronomical community. This paper will elaborate the morphology of electric current flow in low density plasmas, and present several examples observed in cosmic plasmas. The argument is advanced that coaxial current flow is to be expected in cosmic plasmas, though its presence will be difficult to observe remotely. The paper will conclude with suggested observations needed to advance this topic.

2 The magnitude of cosmic electric currents

When electric current flows through astronomical plasmas there must be an electric field that is causing the electric charges to move. The movement of charge will create a circular magnetic field which will constrict the flow of charges into a narrow line. Gravitational attraction will condense the mass of the plasma. The mass of the plasma will be dissipated and expanded by random thermal motions and by the total energy stored in the magnetic field. When all these forces are in a stable state, we set the energies that condense equal to the energies that expand.

Consider an electric current flowing along a tube through a cosmic plasma, the width of the tube is R_0 [7, see eq 2.52]. These expressions are in units of energy per unit length:

$$\frac{\mu_0}{8\pi} I^2(R_0) + \frac{1}{2} Gm^2 N^2(R_0) = \Delta W_{B_z} + \Delta W_k \,. \qquad (1)$$

The integrated linear current density out to radius R_0 is given by I; m is the mean particle mass averaged over electrons, ions, and neutral particles; N is the integrated linear particle number out to radius R_0; ΔW_{B_z} is the difference of magnetic field energy between the total energy inside the tube and that at the boundary of the tube; ΔW_k is the difference of kinetic energy between the total inside the tube and that at the boundary of the tube.

This formulation was proposed by Carlqvist in 1988 [8], showing the relative importance of the electromagnetic force, gravitational force, and thermal motions for any given cosmic plasma setting. Using this relation, Alfven and Carlqvist argue we should expect above the Earth currents on the order of 1.0–10.0 million amperes, which the Iridium satellite network has verified [9]. The relation (1) implies that sunspots and coronal loops should have currents on the order of 10^{11} amps.

Since no satellites yet fly through coronal loops, the magnitude of electric currents are inferred from magnetic fields which are inferred from the polarization of light coming from the regions. Such modelling shows electric currents on the

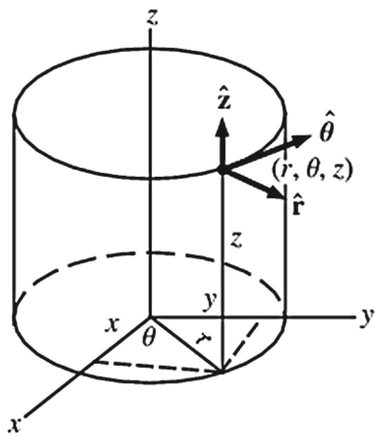

Fig. 1: Geometry for viewing an idealized current flow. Filament runs along the z-axis. Viewer is far away along the y-axis. The $x-z$ plane is the plane of the sky.

order of 10^{11} amperes. For the magnitude of electric current flowing through an entire star — which can be defined as the gravitating mass and the larger magnetic body of the heliosphere — the Carlqvist relation predicts currents on the order of 10^9 amps. This number has been confirmed for the electric current flowing into the Sun along the heliospheric current sheet [10]. The magnitude of the heliospheric current sheet is not directly measured, our existing satellite sensors cannot identify such a low current density, but is inferred from the magnetic fields that exist above and below the plane of the solar system. During the course of the 22-year solar cycle, electric current flows alternately inward/outward radially along the equator, and outward/inward from each pole, closing at the heliosphere, or in some models continuing to the interstellar medium.

Within the interstellar medium, the Carlqvist relation predicts electric currents on the order of 10^{14} amperes. The Planck, Herschel, and SOFIA telescopes have greatly increased the available data for the interstellar medium. Verschuur recently calculated currents of 10^{14} amperes in the A0 molecular cloud through neutral hydrogen emission measurements [11]. Stars form along filaments, the filaments extend for hundreds of light-years without broadening, filaments have a trunk-and-branch morphology, the filaments abruptly change direction at bright points, and different molecular species and energy states are segregated within the filaments. These are all features to be expected from electric currents in a plasma. The cause of these features is not primarily due to gravity.

At the galactic scale, Alfven proposed electric currents should be on the order of 10^{18} amps, from a balance of magnetic pressure, thermal expansion, gravity, and helical magnetic fields. Works by Kronberg and Lovelace [2] and Gabuzda [3] have deduced 10^{18} amperes of current flowing into and out of galaxies in a columnar form. The technique relies on measuring the polarization of light coming from the regions of these jets.

3 Measuring cosmic currents

3.1 Model

In 1950, Lundqvist proposed a force-free current flow in a plasma, meaning that the electric current flowing through the plasma feels no Lorentz force from ambient magnetic fields [12, 13]. This is a very special case, maybe never actually realized in nature, but if there is any truth in the model, it will give predictive power and new insights. In such a lowest energy configuration, the current and magnetic field must be flowing in the same direction. This arrangement of current and magnetic field seen in the force-free flow is much more complicated than a single wire carrying a current with the azimuthal magnetic field curling around.

In equation form, we write for the force-free condition

$$\mu \vec{J} = \alpha \vec{B}\,, \tag{2}$$

where μ and α are scalars which possibly depend upon position and plasma characteristics. $\vec{J}$ is the electric current density vector. $\vec{B}$ is the magnetic field vector. Scott [14] extended Lundqvist's model to values of radius large enough to see reversals of both magnetic and current directions. In the simplest case of current flow in cylindrical symmetry, the solutions to a force-free state are given by Bessel functions J_0 and J_1:

$$B_z(r) = B_z(0)\, J_0(\alpha r)\,, \tag{3}$$

$$B_\theta(r) = B_z(0)\, J_1(\alpha r)\,, \tag{4}$$

$$j_z(r) = \frac{\alpha B_z(0)}{\mu}\, J_0(\alpha r)\,, \tag{5}$$

$$j_\theta(r) = \frac{\alpha B_z(0)}{\mu}\, J_1(\alpha r)\,, \tag{6}$$

where (B_z, B_θ) and (j_z, j_θ) are the (z, θ) directions of the magnetic field and electric current density.

If the electric current is to be in a lowest energy configuration, the electric current and magnetic field flow *in the same direction*, and form a series of concentric shells, like multiple coaxial cables. With increasing R, the current and magnetic field, both pointing in the same direction, twist and eventually flow back in the opposite direction (see Fig 2). That a return current will be present in a lowest energy configuration harkens back to Heaviside's telegraph equation showing that a unidirectional current requires more energy and loses information.

With increasing total current, the direction of flow will again reverse itself, flowing in the direction of the center core. The exact physical conditions that dictate the number of reversals is not yet known. Some magnetic clouds at 1 AU show single reversals with 10^9 ampere currents [15]. Single reversals — simple coaxial — are seen in 10^{18} ampere galactic jets, while multiple reversals are seen in 10^{10} ampere polar currents on Earth. Hence magnitude of current is

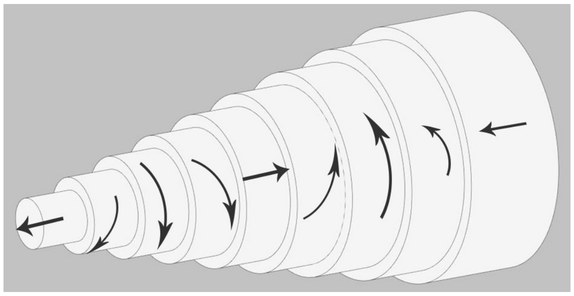

Fig. 2: Coaxial current flow in plasma with multiple reversals. Arrows represent the direction of the magnetic field and the electric current. The magnitudes are given by Eqs. (3)–(6).

not the only factor determining if current is unidirectional or if there is also a return current. The reverse current is also seen in particle-in-cell simulations, where a current injected into a plasma can only continue if a return current is created [7, p. 75].

3.2 Applying the model

Filaments are ubiquitous in the interstellar medium, see Fig. 3 for an example. The Herschel and Planck telescope projects are repositories for hundreds of such images. If electric currents were flowing through the filament, and were doing so according to the coaxial model, how would such a morphology be detected? We will look at several detection techniques: polarization changes due to magnetic fields, Doppler shifts due to relative motion, and segregation of atoms and molecules by ionization potential.

Consider a coaxial filament, with current flow along the z-direction, as shown in Fig 1. The viewer stands far away on the y-axis. The $x - z$ plane is the plane of the sky. We are looking "side-on" towards the filament. Interesting measurements such as changes in light polarization or Doppler shift will depend upon the integrated magnetic field along our line of sight.

We first consider a filament that has current flowing only in one direction, with no return current. Fig. 4 shows the numerically integrated projection of the components of the magnetic field along the y-axis, that is, the line of sight while looking through the filament. For any given point in the filament, the horizontal component of the magnetic field B_x will have a mirror point in front or behind the center which has the opposite horizontal component. Hence all B_x fields will tend to cancel. The B_y values have a different symmetry: fields pointing away on one side of the center will point towards us on the other side of the filament. This is shown in Fig. 4 where the B_y component changes sign on either side of the center. The B_z component will always flow in the positive direction, but drops off to zero at the outer boundary as the flow rotates to a purely azimuthal direction.

Next consider a current flow with a coaxial return flow,

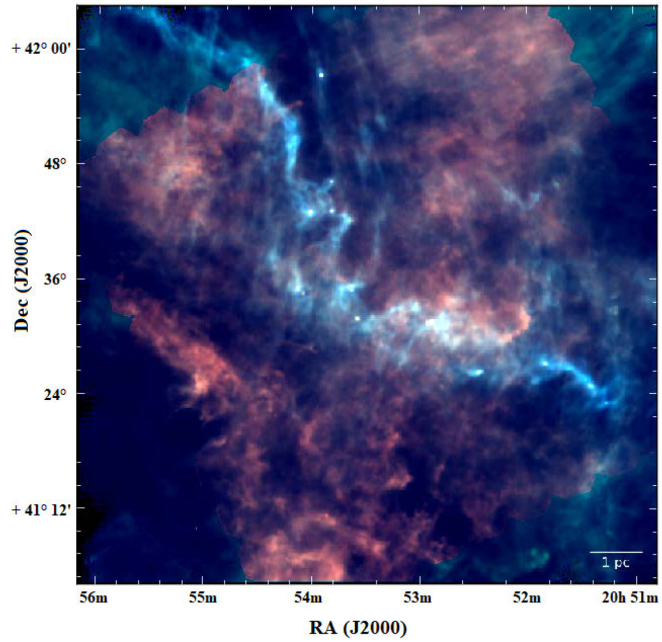

Fig. 3: Gas cloud G82.65-2.00 as seen by the Herschel telescope. RGB image, the colours correspond to Herschel channels at 160 nm (red), 250 nm (green), and 350 nm (blue). Credit ESA/Herschel/M. Juvela [16].

Fig. 5. The central current flow in the positive z-direction is surrounded by a return flow in the negative z-direction. The projection of the magnetic field components is shown. The same symmetries apply as in the previous case, but with more reversals. Figures 4 and 5 were solved on the same scale.

Applying this to telescope observations, low intensity current flow, Fig. 4, will have magnetic fields close to the filament that are parallel to the filament. Those parallel fields will decrease in intensity at the boundary of the filament. More intense current flow, Fig. 5, will show fields along the filament to reverse direction. Observations highlighting the B_y component will appear in Doppler shifts, since flowing charged particles will drag neutral particles. From the observer's point of view, the azimuthal flow around the filament axis will be moving away from the observer on one side of the filament and moving towards the observer on the other side. Look for opposite Doppler shifts on either side of the filament center.

Additional observations should focus on spatial segregation of atoms and molecules. The current flow in the force-free model is also very efficient at collecting ions into shells segregated by ionization potential, see [17]. Spectrographic data can be examined to look for atoms and molecules with low ionization potential collecting near the center of the filament and high ionization potential species concentrated on the periphery.

The ongoing debate as to whether magnetic fields are aligned with or perpendicular to interstellar molecular fila-

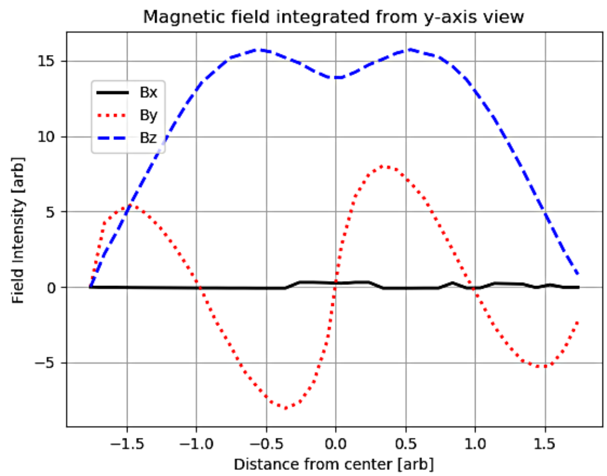

Fig. 4: The x, y, z-components of the integrated magnetic field seen from standing on the y-axis. There is no return current.

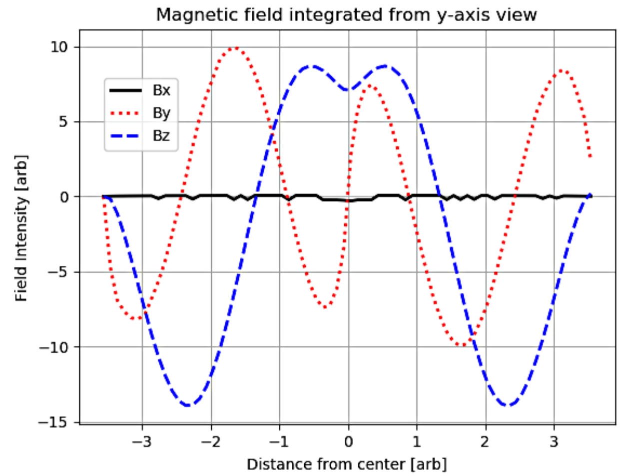

Fig. 5: Same as Fig. 4 but with a return current, that is, a simple coaxial current flow.

ments is rooted in the fact that both are true. The general form of cosmic currents and their associated magnetic fields will be coaxial, with directions constantly shifting from parallel, perpendicular, to anti-parallel, with the number of reversals dependent upon the setting.

As an example on a smaller scale, the polar electric currents on Earth form concentric shells, with the number of shells increasing with the current, see Fig. 6. Imagine trying to estimate the electric current flow in the Earth's aurora, but doing so by observing shifts in the polarization of light passing through the aurora.

When viewed from outside the Earth, the net change in polarization due to magnetic fields will be close to zero. Hence a current flow of billions of amperes can result in very little net change of polarization, and lead to the conclusion that no appreciable electric current exists in the Earth's aurora. It is arguable that planetary polar currents have underlying physics different from the model presented in this paper. If that is so, they still provide a clear example of how increased current causes additional counter-flowing shells and how remote sensing will greatly underestimate the actual current flowing.

The Cassini probe provides another example of how a large current flow can be seen as very small when viewed from a distance. When the Cassini probe flew through the plumes of Enceladus, the Langmuir probe, while flying through the plumes, measured charge densities indicating 10^7 amps of current flowing from the moon towards Saturn. But the magnetometer aboard, measuring from a distance, only measured a magnetic field that would be produced by 10^5 amps. Farrell *et al.* [18] suggest that an ion dust sheath forms around the central flow of electrons, which serves to shield the bulk of current flow. But is is unlikely that these ions are stationary, and more likely that they form a return current of a force-free Birkeland current.

Regardless, this represents a clear case where the electric current inferred from a distance is 1/100th that found through direct measurement. When viewed from the outside, magnetic fields produced by the main central flow will be partly cancelled by the outer sheath flowing in the opposite direction. Remote sensing tends to show only the net current, which in many cases will be much smaller than the number of charges flowing.

The methods described in this paper provide clear qualitative criteria for identifying force-free currents in cosmic plasmas. The more quantitative Carlqvist relation (1) can be used in a wide variety of cosmic settings. We suggest that the voluminous data of filaments in the interstellar medium available in Herschel, Planck, VLA, HI4PI, and other surveys be examined using the Carlqvist relation to map the morphology of electric currents in the galaxy. The method for such analysis, assuming unidirectional current flow, is presented clearly in [11]. Extending that method to the more general case of coaxial current flow will be the subject of a future paper.

The primary observational requirement, to apply the methods in this paper, is high resolution polarization and hyperspectral data cube with beam width easily resolving 0.1 pc distance, which is the average ISM filament width. Interstellar filaments in regions of high star formation are likely candidates, such as protostars in filaments in the Orion A molecular clouds: RA [42:00.00 to 34:00.00] Dec [-9:00:00 to -5:00:00].

4 Conclusions

Electric currents are ubiquitous in cosmic plasmas, having been observed at the planetary, solar, interstellar, and galactic levels. Considerations from basic plasma physics lead us to expect that in cosmic settings, electric current will flow in a coaxial form: a primary current flow will be matched by a surrounding return current. There may even be multiple

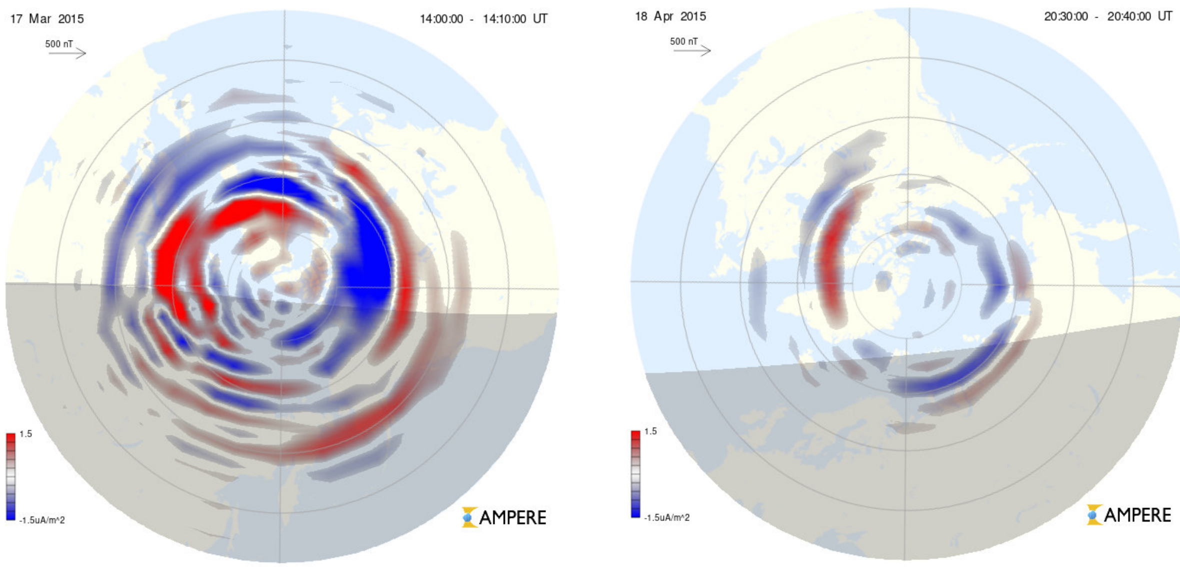

Fig. 6: Earth's polar electric currents. Left, from the "St Patrick's Day Storm" of 2015. Right, from one month later during quiet solar wind. Red/Blue represents current flowing away/towards the planet. During active solar wind there are multiple concentric reversals. From http://ampere.jhuapl.edu/ for the specified dates.

reversals of current, as in planetary polar currents.

When light passes through a coaxial current, the polarization changes will tend to cancel out, making it very difficult to determine the actual amount of current flowing. Likewise, any magnetic field measurements taken from outside such a coaxial current tube will greatly underestimate the current, since the reversing directions of current flow will cause a cancellation of magnetic field strength as seen from the outside. The ongoing debate as to whether magnetic fields are aligned with or perpendicular to interstellar molecular filaments is rooted in the fact that both are true.

Force-free current flow can also be identified from Doppler shift morphology and the segregation of atoms and molecules by ionization potential. The wealth of recent high resolution data in infrared, millimeter, and radio frequencies can be examined to distinguish different models for the flow of electric currents in cosmic plasmas.

5 Acknowledgements

This work was not funded. The author wishes to thank Don Scott for his work on coaxial plasma current flow, and Prof Richard Lovelace of Cornell University for his encouragement to write this article.

Submitted on May 8, 2025

References

1. Alfven H. and Carlqvist P. Interstellar clouds and the formation of stars. *Astrophysics and Space Science*, 1978, v. 55 (2), 487–509.
2. Kronberg P. and Lovelace R. Extragalactic circuits, transmission lines, and CR particle acceleration. arXiv: astro-ph/1412.3835.
3. Gabuzda D., Nagle M. and Roche N. The jets of AGN as giant coaxial cables. *Astrophysics and Astrophysics*, 2018, v. 612, A67.
4. Birkeland K. The Norwegian Aurora Polaris Expedition, 1902-03. Vol. I.: On the Cause of Magnetic Storms and the Origin of Terrestrial Magnetism. Christiania H Aschehoug and Co., 1913.
5. Zmuda A. J., Armstrong J. C. and Heuring F. T. Characteristics of transverse magnetic disturbances observed at 1100 kilometers in the auroral oval. *Journal of Geophysical Research*, 1970, v. 25 (75), 4757–4762.
6. Nahin P. Oliver Heaviside: The Life, Work, and Times of an Electrical Genius of the Victorian Age. Johns Hopkins University Press, Baltimore, MD, 2002.
7. Peratt A. Physics of the Plasma Universe. Springer Science+Business Media, New York, 2015.
8. Carlqvist P. Cosmic electric currents and the generalized Bennett relation. *Astrophysics and Space Science*, 1988, v. 144 (1–2), 73–84.
9. Coxon J. C., Milan S. E., Clausen L. B. N., Anderson B. J., and Korth H. The magnitudes of the regions 1 and 2 Birkeland currents observed by AMPERE and their role in solar wind-magnetosphere-ionosphere coupling. *Journal of Geophysical Research (Space Physics)*, 2014, v. 119 (12), 9804–9815.
10. Israelevich P. L., Gombosi T. I., Ershkovich A. I., Hansen K. C., Groth C. P. T., DeZeeuw D. L., and Powell, K. G. MHD simulation of the three-dimensional structure of the heliospheric current sheet. *Astronomy and Astrophysics*, 2001, v. 376, 288–291.
11. Verschuur G. High-resolution observations and the physics of high-velocity cloud A0. *Astrophysical Journal*, 2013, v. 766 (113), 1–17.
12. Lundquist S. Magneto-hydrostatic fields. *Ark. Fys.*, 1950, v. 2, 361–365.
13. Lundquist S. On the stability of magneto-hydrostatic fields. *Phys. Rev.*, 1951, v. 83, 307–311.
14. Scott D. Birkeland currents: A force-free field-aligned model. *Progress in Physics*, 2015, v. 11 (2), 167–179.
15. Lepping R. P., Berdichevsky D. B, Wu C. C., Szabo A., Narock T., Mariani F., Lazarus A. J., and Quivers A. J. A summary of WIND magnetic clouds for years 1995-2003: model-fitted parameters, associated errors and classifications. *Annales Geophysicae*, v. 24 (1), 215–245.

16. Saajasto M., Juvela M., *et al.* Correlation of gas dynamics and dust in the evolved filament G82.65-02.00. *Astronomy and Astrophysics*, v. 608, A21.

17. Marklund G. T. Plasma convection in force-free magnetic fields as a mechanism for chemical separation in cosmical plasmas. *Nature*, 1979, v. 277 (5695), 370–371.

18. Farrell W. M., Wahlund J. E., *et al.* Ion trapping by dust grains: Simulation applications to the Enceladus plume. *Journal of Geophysical Research* (*Planets*), 2017, v. 122 (4), 729–743.