Magnetically-Aligned Interstellar Dust Grains at the Heliosphere

To cite this article: P C Frisch 2018 J. Phys.: Conf. Ser. 1100 012011

View the article online for updates and enhancements.
Magnetically-Aligned Interstellar Dust Grains at the Heliosphere

P C Frisch

1 Department of Astronomy and Astrophysics, University of Chicago, Chicago IL 60637 USA
E-mail: frisch@oddjob.uchicago.edu

Abstract. Light from nearby stars becomes linearly polarized while traversing a dichroic interstellar medium. Polarization data which reveal heliosphere features are summarized. Polarizing dust grains trace a magnetic field direction consistent with the field affecting the warm breeze of secondary interstellar helium found by IBEX. Polarization data also trace the field direction that dominates the configuration of the IBEX ribbon of energetic neutral atoms (ENA). The polarizations that echo heliospheric features appear to arise from magnetically-aligned submicron interstellar dust grains that are excluded from the inner heliosphere by large charge-to-mass ratios, but, due to long collision times, retain their alignment with respect to the interstellar magnetic field draping over the heliosphere.

1. Introduction
The low density interstellar material around the heliosphere sustains a magnetic field that aligns interstellar dust grains and creates a dichroic medium capable of polarizing the light of background stars. These linear polarizations are parallel to the direction of the interstellar magnetic field (ISMF) producing the alignment [1]. The polarizations thus map the direction of the ISMF. The high sensitivities now achievable with modern polarimeters, capable of detecting polarization strengths of 0.001% or less, permit mapping of the ISMF formed in the local interstellar medium (ISM) where column densities are low, $N(H^0) < 10^{18.5}$ [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21].

A survey of polarized starlight tracing the local interstellar magnetic field (ISMF) is underway [22] in order to connect the ambient interstellar magnetic field with the ISMF that shapes the heliosphere, orders the ribbon of energetic neutral atoms [23, 24, 25], and deflects the ions giving rise to the warm breeze of secondary neutral atoms [26, 27, 28] discovered by IBEX. Results of the study reveal an imprint of heliosphere geometry on the polarization data. One feature is a filament of aligned interstellar dust grains with a magnetic pole corresponding to the upwind direction of the warm breeze of neutral He discovered by IBEX (Figure 1, [15]). A second feature is a band of statistically probable magnetic field directions that echoes the heliosphere geometry [22].

The interstellar cloud surrounding the heliosphere provides the source of the “interstellar wind” feeding interstellar gas and dust into the inner heliosphere, and is termed here as the

1 These features are ordered by the B-V plane, formed by the directions of the interstellar magnetic field B from the IBEX “ribbon” of interstellar neutral atoms and the velocity of the flow of primary interstellar neutral atoms through the heliosphere [28].
circumheliospheric interstellar material (CHM). The name “Local Interstellar Cloud” (LIC) is used to describe the cloudlet in the 15-cloud model of Redfield and Linsky [29]. The nose of the heliosphere, located 16° northeast of the galactic center [30], is outside of the LIC as defined in the 15-cloud model (Figure 19 in [29]).

The context for the ISMF surrounding the heliosphere is provided by radio continuum [31] and H\(^\text{II}\) 21-cm data [32] that show giant shells associated with the Loop I superbubble. We assume spherical shells, which places the Sun in the rim of the Loop I superbubble. The bulk motion of the local interstellar clouds through the Local Standard of Rest (LSR) is directed away from the center of the Loop I superbubble [33, 34]). IBEX data on the interstellar He\(^{\text{II}}\) velocity in the inner heliosphere, and the ISMF direction from the center of the IBEX ENA ribbon, indicate that the velocity of the CHM through the LSR is perpendicular to the orientation of the interstellar magnetic field [35].

2. Interstellar Boundary Conditions of the Heliosphere

Determining the interstellar boundary conditions of the heliosphere requires identifying a star with an absorption component at the CHM velocity projected onto the stellar sightline. Interstellar absorption lines in that component then provide data on the composition and ionization of the pristine CHM. Neutral atoms from the CHM enter the heliosphere, become ionized and reprocessed, to produce the pickup ions and anomalous cosmic ray particle populations. These populations provide boundary conditions for radiative transfer models of the surrounding interstellar gas, after accounting for the filtration of neutral interstellar atoms in heliosheath regions [36]. Slavin and Frisch (2008) found that the predicted ionization levels of H, He, N, O, and Ne depend in detail on the interstellar radiation field in the range 500Å–1500Å, the total interstellar cloud opacity to penetrating radiation, and the properties of the soft X-ray background component that maintains the He and Ne ionization. The composition of interstellar dust grains in the CHM is inferred from the atoms not seen in the gas phase.

In situ measurements of interstellar He\(^{\text{II}}\) atoms in the inner heliosphere yield the CHM velocity vector, which relates the CHM to interstellar clouds observed through the absorption lines they create in the spectra of nearby stars. Reconstruction of the trajectories of the atoms through the heliosphere, after taking into account gravitational forces and weak ionization effects, yields the upwind direction for the flow of CHM through the heliosphere. In the inertial frame of the heliosphere the interstellar helium gas velocity arrives from the direction \(\ell = 3.66^\circ \pm 0.94^\circ\), \(b = 15.05^\circ \pm 1.22^\circ\), with a velocity of \(25.4 \pm 1.1\) km s\(^{-1}\) and temperature of \(7,260 \pm 270\) K [30, 37, 38].

The velocity vector of interstellar grains flowing through the heliosphere has been determined from Ulysses dust data to have a similar upwind direction (\(\ell = 8.0^\circ \pm 10^\circ\), \(b = 13.5^\circ \pm 5^\circ\) [40]) and velocity (\(24.5^{+0.11}_{-0.12}\) km s\(^{-1}\) [41]) as the gas.

The LIC component observed toward the “Dog Star”, Sirius\(^3\), is the interstellar cloud containing the CHM. Projecting the CHM velocity toward the direction of Sirius, 137° away from the nose of the heliosphere, yields a velocity of \(-18.6 \pm 0.8\) km s\(^{-1}\). The projected CHM velocity coincides with the velocity of the LIC component in the spectrum of Sirius (\(-17.6 \pm 1.5\) km s\(^{-1}\) [43]), which firmly links the CHM to the LIC cloud in front of Sirius.

The boundary conditions of the heliosphere have been modeled by Slavin and Frisch (2008, [36]) using radiative transfer models of the ionization of the LIC component that is measured toward epsilon CMa [44], located 12.6° away from Sirius. Both Sirius and the more distant star epsilon CMa show the same two interstellar neutral clouds. The LIC radiative transfer

\(^2\) It is a curiosity that for the relative Sun-CHM velocity of 25.4 km s\(^{-1}\) the Sun will have traveled over 1334 AU (or 0.006 pc) through the CHM since Sir William Herschel first determined the proper motion of the Sun through space [39].

\(^3\) Sirius has been referred to as the Dog Star since the days of Homer [42].
models utilize a range of assumptions, and include predictions of the neutral helium densities and temperatures at the heliosphere boundaries in agreement with IBEX and Ulysses data [38, 37]. The observed temperature of the LIC component toward Sirius (7000–8500 K) represents interstellar gas over the integrated sightline through the cloud, and is consistent with the interstellar He$^+$ temperature K derived from in situ IBEX measurements [30, 37, 38].

Reconstructed cloud abundances from the radiative transfer models [36] give the composition of the interstellar dust grains in the CHM based on the “missing mass” principle, where atoms not found in the gas phase are assumed to be captured by the interstellar dust grains in the same cloud. These models indicate that the dust grains in the LIC are composed primarily of olivines, and that Mg, Si, and Fe are strongly depleted onto the LIC interstellar grains, O is moderately depleted, and C and S are not present in the grains4 (also see [33]).

The LIC dust grain composition inferred from the radiative transfer models of the LIC cloud toward epsilon CMa [36] are in agreement with the LIC interstellar dust grain composition measured by the CDA instrument on Cassini in orbit around Saturn [46]. Both investigations find the interstellar dust grains in the cloud around the heliosphere lack a carbonaceous component, and are dominated by silicate oxides. Cassini measured 36 interstellar grains and found magnesium-rich grains with a silicate and oxide composition and iron-rich inclusions. Similar grain compositions were found from the radiative transfer models. The models show that the amount of carbon predicted by cosmic abundances is found in the interstellar gas, within nothing left for dust grains. The high abundances of refractory elements in interstellar dust grains is attributed to the processing of interstellar grains through shock fronts that erode the volatile grain components [47, 40] and also decrease the average size distribution of dust grains.

3. Extinction and Small Grains
The spectral dependence of the linear polarization strengths provide a diagnostic of the dimensions of the polarizing grains. Marshall et al. [18] have shown that the maximum polarization towards nearby stars tends to occur at shorter (bluer) wavelengths than found for more obscured distant stars, giving wavelength of maximum polarization $\lambda_{\text{max}} \sim 0.315$ $\mu\text{m}$. The smaller grains implied by this value, radius $a \sim 0.05$ $\mu\text{m}$, are consistent with shocked grains in the low density local interstellar material. Fortunately polarization position angles are independent of grain size [48].

Czechowski & Mann [49] have shown that the ratio of the Larmor radius of the grain to the thickness of the outer heliosheath governs the trajectories of interstellar dust grains through the heliosheath regions, with only a very small fraction of the smallest grains likely to reach the inner-most heliosphere [50, 51, 52]. Figure 3 in Frisch et al. (1999) [40] indicates that carbonaceous grains with radii $\sim 0.05$ $\mu\text{m}$ have gyroradii $\sim 10$ AU in the heliopause region. Increasing grain density by 50% to account for the probable silicate composition still results in the exclusion of the smallest interstellar dust grains.

Silicate grains with radii of $\sim 0.05$ $\mu\text{m}$ have high surface potentials in the outer heliosheath region ($\sim 5–10$ V) that will lead to tight coupling between the ISDGs and the deflected ISMF in the outer heliosheath region [53]. For comparison, this distance interval is significantly smaller than the thickness of the inner heliosheath in the directions of Voyager 1 (27 AU) and Voyager 2 (larger than 31 AU), and significantly smaller than the 2000 AU scale of the outer heliosheath derived from the properties of the magnetic turbulence detected by Voyager 1 [54].

The interstellar dust population interacting with the heliosphere thus contains ample abundances of micron-sized dust grains that both are excluded from entering the heliosphere

4 This argument for grain composition breaks down when grain gyroradii are larger than the cloud. Gruen and Landgraf [45] show that large interstellar dust grains, with masses larger than $10^{-15}$ gr., have large gyroradii and couple to interstellar clouds over length scales of 100-1000 pc.
Figure 1. A filament of interstellar dust grains interacting with the heliosphere has been identified in the polarizations of stars within 40 pc [15]. The best-fitting ISMF to the polarizations of the stars forming the polarization filament is directed toward $\ell=357.3^\circ$, $b=17.0^\circ$ ($\pm11.2^\circ$) (black cross). and magnetic turbulence appears to account for $9.6^\circ$ of the direction uncertain. The axis of the polarization filament makes an angle of $80^\circ \pm 14^\circ$ with respect to the fundamental B-V symmetry plane of the heliosphere, for surrounding magnetic field direction B and inflowing interstellar velocity V. The confluence of the ISMF traced by the polarization filament and the warm breeze of secondary interstellar He$^0$ discovered by IBEX [57, 26, 27] strongly suggest that interstellar dust grains interacting with the heliosphere are responsible for the polarization filament.

(Section 6) and also have compositions consistent with those of magnetically aligned grains elsewhere (e.g. [55]).

4. Geometric Imprint of the Heliosphere on Polarized Starlight
Linearly polarized starlight provides the only means of detecting the ISMF direction over short sightlines through very low density interstellar material such as surrounds the heliosphere. We have undertaken to study the local interstellar magnetic field through the collection and analysis of linear polarization data of stars within 40 pc [56, 8, 14, 15, 17, 20, 18, 19].

Linear polarization data for each star trace the projection of the three-dimensional polarization vector onto the plane of the sky so that a statistical combination of the polarization data reconstructs the missing radial component of the polarizations. Combining multiple measurements of polarization position angles thus allows the directions of the magnetic field to be mapped throughout the sky. A surprising outcome of our polarization survey is that the interaction between the heliosphere and interstellar medium leaves an imprint on the linear polarizations of stars within $\sim 15$ pc, including a polarization filament [15] and polarization band [22].

The low densities of interstellar gas near the Sun [33] indicate an absence of dense clouds that often show strongly polarized starlight. Thus the low local densities also enable the detection of weak polarization features arising from the interaction between the heliosphere and the interstellar medium [22].

ISMF direction of IBEX Ribbon: The direction of the interstellar magnetic field traced by the center of the IBEX Ribbon [23, 25] was recovered from measurements of linearly polarized
starlight for stars within 40 pc, based on a merit function that statistically minimized the sine of polarization position angles. The best-fitting ISMF direction was directed toward $\ell=36.2^\circ$, $b=49.0^\circ$ ($\pm16^\circ$). The IBEX Ribbon ISMF direction was recovered after omitting a set of data that trace an independent filament of polarizations (below). For comparison, the weighted mean center of the IBEX Ribbon is located at $\ell = 36.7^\circ \pm 2.1^\circ$, $b = 56.0^\circ \pm 0.6^\circ$ [58].

**Filament of Polarization:** A polarization filament has been identified with a best-fitting ISMF direction aligned with the direction of the warm breeze of magnetically deflected helium atoms (Figure 1, [15]). The coincidence between the filament ISMF direction and the warm breeze of secondary interstellar He$^0$, which forms from magnetically deflected helium ions [57, 26, 27], is the basis for concluding that the filament is formed by interstellar dust grains in the upwind outer heliosheath. The filament star polarizations trace a magnetic field oriented toward ecliptic coordinates $\lambda=255.0^\circ \pm 7.0^\circ$, $\beta=7.9^\circ \pm 8.5^\circ$, in agreement with the warm He$^0$ breeze direction of $\lambda,\beta=251^\circ, 12.0^\circ \pm 7.8^\circ$. The warm He$^0$ breeze arises from secondary helium atoms created from charge-exchange between the parent interstellar helium ions that are magnetically deflected in the outer heliosheath regions and subsequently reneutralized before propagating to the inner heliosphere. Both the filament magnetic pole and warm breeze upwind direction appear to trace the magnetic deflection of charged particles in the magnetic field in outer heliosheath regions.

**Polarization band:** A “band” of overlapping polarization position angles has been identified by a great circle on the sky that traverses the heliosphere nose and has a best-fitting ISMF direction toward the ecliptic poles. The properties of this band are under study [22].

**Low frequency radio emissions:** Figure 1 shows the locations of the dozen low frequency ($\sim 2 - 3$ kHz) radio emissions originating in the ionized interstellar gas beyond the heliopause, and located by the triangulation of radio signals received by Voyagers 1 and 2 [59]. Half of the 3 kHz emissions are located in the directions of the polarization filament (Figure 1). The ISMF traced by the filament polarizations may provide for the propagation of Langmuir waves into the upstream interstellar electron plasma where the oscillation frequency of the plasma at density $n_e=0.08$ cm$^{-3}$ produces the 3 kHz emissions [60, 61].

5. Retention of Magnetic Alignment of ISDGs Interacting with Heliosphere

The polarization data discussed here suggest that the magnetic alignments of the charged, optically asymmetric, interstellar grains that are trapped in the ISMF interacting with the heliosphere must be preserved during the interaction so that grains retain their alignment. The IBEX ribbon of enhanced ENA fluxes [58] provides a remote diagnostic of the orientation of the ISMF interacting with the heliosphere. The ribbon is seen in directions where the ISMF that is draping over the heliosphere is perpendicular to the radial sightlines, as viewed from the 1 AU orbit of IBEX [24, 25]. The existence of the IBEX ribbon requires that the ISMF interacting with the heliosphere smoothly varies in the outer heliosheath in the upwind directions.

6. Filament Polarizations and Exclusion of Submicron Grains from Heliosphere

The dusty component of the LIC contains grains with masses ranging from $10^{-15} - 10^{-9}$ gr [40, 53, 62], or larger if micro-meteorites detected by radar are included [63]. In situ measurements of interstellar dust grains by Ulysses and Galileo (Section 6) show a steep decrease in the numbers of grains as grain mass decreases, including a lack of grains with radii less than 0.18 $\mu$m compared to a nominal MRN [64] interstellar distribution [40, 65, 62]. The smallest grains are deflected away from the dust flow at the heliopause region, where the grain potentials are increased by interactions with heliosheath plasma that include the enhanced ejection of secondary electrons from the smallest particles embedded in the million degree plasma (see Figure 2 in Slavin et al. 2012). Grain charging and deflection will increase if the interstellar grains are porous and not compact [66]. Orbits of the smallest dust grains deflected around the
heliosphere by Lorentz forces are shown in [67, 53]. These small deflected grains are a plausible origin for the polarizing dust grains traced by the polarization filament.

In situ grain measurements by Ulysses and Galileo give data on the grain trajectories and mass distribution [68, 69, 40, 63, 51, 62]. The dominant features of the grain mass distributions are the deficit of low mass grains and grains with larger masses than predicted by the typical MRN interstellar grain mass distributions. For silicate grains the deficit sets in for grain radii below $\sim 0.3 \, \mu m$ and the excess appears for grain radii larger than $\sim 1.0 \, \mu m$ [40, 62]. The missing grain mass varies with solar cycle phase due to the filtration of submicron interstellar grains interacting with the solar wind.

The gas-to-dust mass ratios determined from the in situ measurements appears to vary over time, possibly due to variations in the filtration of the smallest grains. The gas-to-dust mass ratio, $R_{g/d}$, found for the grains detected by Ulysses and Galileo during the decade of the 1990’s is 94 (+46, -38), based on an interstellar gas density of 0.3 cm$^{-3}$ [40, 51]. The entire sixteen years of the Ulysses data set (1992–2008) yielded $R_{g/d}$=193 (+85, -57), based on a slightly lower interstellar density (0.247 cm$^{-3}$) and a CHM velocity of 26 km s$^{-1}$[5]. In order to compare the $R_{g/d}$ value for the 1990’s and the $R_{g/d}$ value for the full 16 years of data, the latter value should be adjusted upwards by 45% to account for the differences in the assumed gas densities and for the velocity dependence of the Ulysses impact ionization detector [62]. There remains a significant difference between the values for $R_{g/d}$ found during the measurements in the 1990’s and the total sixteen years of measurements.

The difference between the $R_{g/d}$ for the 1990’s and full 16 years is likely due to variations in the polarity of the solar wind between the 1990’s and the first decade of the 21st century. During the 1990’s the solar cycle magnetic polarity acted to “focus” interstellar dust grains toward the plane of the ecliptic [65], which has the effect of decreasing the gas-to-dust mass ratios obtained from data at 1 AU during that decade, compared to later values based on both phases of solar magnetic polarities [62]. The signature of the solar magnetic cycle on the gas-to-dust ratios provides additional support to the view that the small grains are filtered from the interstellar flow in the outermost heliosphere and heliosheath where the deflection of polarizing interstellar dust grains around the heliosheath would occur.

Slavin et al. [51] predict that time-variable submicron-sized grains are deflected in the outer heliosphere and heliosheath regions and form plumes around the heliosphere for the defocusing phase of the solar cycle. Sterken et al. [52] suggested that additional filtration of small grains in the outer heliosheath is needed to explain the Ulysses observations of grains. The deflection of small grains with large charge-to-mass ratios at the heliopause is supported by the in situ measurements of interstellar dust (also see review of Mann [70]).

7. Closing Remarks
The similar interstellar magnetic field directions traced by the polarization filament [15] and warm breeze of neutral helium flowing through the heliosphere [26], and the imprint of the heliospheric geometry on a statistically defined polarization band [22], indicate that magnetically aligned interstellar dust grains interacting with the heliosphere produce visible polarizations. The polarization data indicate that submicron-sized dust grains with an interstellar origin are trapped on the interstellar magnetic field lines draped over the heliosphere (Figure 1).

Magnetometers on board Voyager 1 have measured the ISMF in the outer heliosheath [6] and found a strength of 5 $\mu$G and laminar flow [71]. During quiet intervals, outside of disturbances from solar storms, the magnetic field direction was displaced toward the center of the IBEX ribbon [28]. These characteristics in the inner regions of the outer heliosheath suggests an

---

5 The grain velocity affects the interpretation of the grain mass distribution) [62].
6 Voyager 1 is presently located about 30° to the ecliptic north of the heliosphere nose.
orderly magnetic field. Further out, Voyager 1 found an outer scale of turbulence of $\sim 0.01$ pc, which is thought to represent the distance to the undisturbed interstellar medium [54]. The outer scale of turbulence corresponds to the maximum allowed thickness for the location of the aligned dust grains that create the polarization filament.

The orderly nature of the ISMF allows the polarizing ISDGs to retain their alignment during their approach through the outer heliosheath. The extremely low volume densities of the CHM gas, $< 0.3 \text{ cm}^{-3}$, means that grain alignment is disrupted by collisions with gas over timescales of millions of years.

The results showing that aligned interstellar dust grains trace the interaction between the heliosphere and interstellar magnetic field suggests that the long-term monitoring of weakly polarized light of nearby stars can monitor the outer heliosheath regions and possibly provide the first evidence of changes in the galactic environment of the Sun.

Acknowledgements. The author is grateful for support by the Interstellar Boundary Explorer mission as a part of the NASA Explorer Program.

References

[1] Andersson B G, Lazarian A and Vaillancourt J E 2015 ARA&A 53 501–539
[2] Magalhaes A M, Rodrigues C V, Margoniner V E, Pereyra A and Heathcote S 1996 Polarimetry of the Interstellar Medium (Astronomical Society of the Pacific Conference Series vol 97) ed W G Roberge & D C B Whittet pp 118–+
[3] Pirola V, Berdyugin A, Mikkola S and Coyne G V 2005 ApJ 632 576–589
[4] Pereyra A and Magalhães A M 2007 ApJ 662 1014–1023 (Preprint arXiv:astro-ph/0702550)
[5] Pirola V, Vornanen T, Berdyugin A and Coyne G V S J 2008 ApJ 684 558–568 (Preprint 0805.4289)
[6] Wiktorowicz S J and Matthews K 2008 PASP 120 1282–1297 (Preprint 0810.5561)
[7] Bailey J, Lucas P W and Hough J H 2010 MNRAS 405 2570–2578 (Preprint 1003.1753)
[8] Frisch P C, Andersson B G, Berdyugin A, Pirola V, DeMatigre R, Funsten H O, Magalhaes A M, Seriacopi D B, McComas D J, Schwadron N A, Slavin J D and Wiktorowicz S J 2012 ApJ 760 106
[9] Pirola V, Berdyugin A and Berdyugina S 2014 Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series (Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series vol 9147) p 8
[10] Berdyugin A, Pirola V and Teerikorpi P 2014 A&A 561 A24
[11] Wiktorowicz S J, Nofi L A, Jontof-Hutter D, Koppa P, Laughlin G P, Hermis N, Yung Y L and Swain M R 2015 ArXiv e-prints (Preprint 1507.03588)
[12] Bailey J, Kedziorek-Chudczak L, Cotton D V, Bott K, Hough J H and Lucas P W 2015 MNRAS 449 3064–3073 (Preprint 1503.02236)
[13] Wiktorowicz S J and Nofi L A 2015 ApJ 800 L1 (Preprint 1412.6117)
[14] Frisch P C, Berdyugin A, Pirola V, Magalhaes A M, Seriacopi D B, Wiktorowicz S J, Andersson B, Funsten H O, McComas D J, Schwadron N A, Slavin J D, Hanson A J and Fu C W 2015 ApJ 814 112 (Preprint ArXiv:1510.04679)
[15] Frisch P C, Andersson B G, Berdyugin A, Pirola V, Funsten H O, Magalhaes A M, Seriacopi D B, McComas D J, Schwadron N A, Slavin J D and Wiktorowicz S J 2015 ApJ 805 60 (Preprint 1503.00358)
[16] Marshall J P, Cotton D V, Bott K, Ertel S, Kennedy G M, Wyatt M C, del Burgo C, Absil O, Bailey J and Kedziorek-Chudczak L 2016 ApJ 825 124 (Preprint 1604.08286)
[17] Cotton D V, Bailey J, Kedziorek-Chudczak L, Bott K, Lucas P W, Hough J H and Marshall J P 2016 MNRAS 455 1607–1628 (Preprint 1509.07221)
[18] Marshall J P, Cotton D V, Bott K, Ertel S, Kennedy G M, Wyatt M C, del Burgo C, Absil O, Bailey J and Kedziorek-Chudczak L 2016 ApJ 825 124 (Preprint 1604.08286)
[19] Bailey J, Cotton D V and Kedziorek-Chudczak L 2017 MNRAS 465 1601–1607 (Preprint 1611.01596)
[20] Cotton D V, Marshall J P, Bailey J, Kedziorek-Chudczak L, Bott K, Marsden S C and Carter B D 2017 MNRAS 467 873–897 (Preprint 1701.02890)
[21] Cotton D V, Bailey J, Howarth I D, Bott K, Kedziorek-Chudczak L, Lucas P W and Hough J H 2017 Nature Astronomy 1 690–696
[22] Frisch P C, Berdyugin A, Pirola V, Cole A, Hill K, Harlingten C, Magalhaes A M, Seriacopi D B, Ferrari T, Ribeiro N L, Wiktorowicz S J, Cotton D V, Bailey J, Kedziorek-Chudczak L, Marshall J P, Bott K, Santos F, Helies C, McComas D J, Funsten H O, Schwadron N A, Livadiotis G and Redfield S 2018 ApJ, submitted
[61] Gurnett D A, Kurth W S, Burlaga L F and Ness N F 2013 Science 341 1489–1492
[62] Krueger H, Strub P, Sterken V J and Grün E 2015 ApJ 812 140
[63] Landgraf M, Baggaley W J, Grün E, Krüger H and Linkert G 2000 J. Geophys. Res. 105 10343–10352
[64] Mathis J S, Rumpl W and Nordsieck K H 1977 ApJ 217 425–433
[65] Landgraf M 2000 J. Geophys. Res. 105 10303–10316
[66] Ma Q, Matthews L S, Land V and Hyde T W 2013 ApJ 763 77 (Preprint 1210.0459)
[67] Mann I and Czechowski A 2004 AIP Conf. Proc. 719: Physics of the Outer Heliosphere pp 53–58
[68] Grün E, Gustafson B, Mann I, Baguhl M, Morfill G E, Staubach P, Taylor A and Zook H A 1994 A&A 286 915–924
[69] Baguhl M, Grün E, Hamilton D P, Linkert G, Riemann R, Staubach P and Zook H A 1995 Space Sci. Rev. 72 471–476
[70] Mann I 2010 ARA&A 48 173–203
[71] Burlaga L F and Ness N F 2016 ApJ 829 134