Testing the H-wave Hypothesis for the Origin of the IBEX Ribbon

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Abstract. The Interstellar Boundary Explorer (IBEX) spacecraft maps the neutral atom fluxes across the whole sky. Thereby it is indirectly mapping the structure of the outer heliosphere and the (very) local interstellar medium. A particularly interesting feature in the IBEX-Hi all-sky maps of the differential flux of Energetic Neutral Atoms (ENAs) in the 0.7 to 4.3 keV range is the so-called ribbon, i.e. a factor of two to three enhancement in a twenty to thirty degree wide band across the sky. Amongst other hypotheses it has been argued that this ribbon may be related to a neutral density enhancement, a so-called H-wave, in the local interstellar medium. By employing an analytical model of the large-scale structure of the heliosphere it is demonstrated that the H-wave scenario for the ribbon formation leads to results that are fully consistent with the observed location of the ribbon in the full-sky maps as well as in space at all energies detected with IBEX-Hi. As a further extension to previous work and as a necessary prerequisite for the computation of differential ENA fluxes, the evolution of the proton velocity distribution function in the inner heliosheath is semi-analytically computed in terms of a κ-functions with locally determined κ-values.

1. Introduction

The most unexpected feature in the all-sky maps of the differential fluxes of energetic neutral (hydrogen) atoms (ENAs) is the so-called 'ribbon' [1]. In this band the ENA fluxes are two- to three-fold higher than the globally-distributed 'background' fluxes [2]. Even after now seven years since its discovery [3], there is no generally accepted model for the formation of the ribbon.

After at least one ribbon model had to be discarded [4], the remaining ones can be ordered into two groups. According to the first and so far more popular one, the ribbon ENAs are produced from charge exchange processes in the outer heliosheath (OHS), i.e. in the disturbed interstellar flow beyond the heliopause (see, e.g., [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]). The second group consists of those models that assume the ribbon ENAs to be generated in the inner heliosheath (IHS), i.e. between the solar wind termination shock and the heliopause (see, e.g., [16, 17, 18, 19, 20, 21]).

The present paper deals with the second group. It is, first, re-emphasized that - independent of the details of any model belonging to this group - if the ribbon ENAs are produced in the IHS, they must originate in a predestined, favourable region there. Second, it is shown that such models are consistent with the available observations. And since any such model needs

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to consider the seed population of the ENAs in order to provide differential fluxes, we discuss, third, a model for the evolution of the joint thermal (solar wind) and suprathermal (pick-up) proton velocity distribution in the IHS.

2. A simplified model of the heliosphere

For a number of purposes it is sufficient to consider an analytical representation rather than a numerical simulation of the large-scale flow structure of the heliosphere, for recent examples see [22, 23, 24]. Following the original idea by Parker [25], most of such analytical approaches formulate the overall plasma flow in terms of a velocity potential that consists of two sources, namely a spherically symmetric one at the origin representing the solar wind and a homogeneous one at infinity representing the interstellar flow with velocity $\vec{u}_{ISM}$. Such model can be expected to be a reasonable approximation in the nearly incompressible region between the termination shock and the bow shock [26, 27]. From the specific representation [23, 21] in cylindrical coordinates ρ and z

$$\mathbf{u}(\mathbf{r}) = -\nabla\Phi(\mathbf{r}) \quad ; \quad \Phi(\mathbf{r} = \rho\mathbf{e}_\rho + z\mathbf{e}_z) = |\vec{u}_{ISM}| \left(z + \frac{2}{r}\right) \quad ; \quad r = |\mathbf{r}| = \sqrt{\rho^2 + z^2} \tag{1}$$

follow the flow lines (parameterized with η) as

$$z(\rho) = \left(\eta - \frac{\rho^2}{4}\right)\rho\left(1 - \left[\eta - \frac{\rho^2}{4}\right]^2\right)^{-\frac{1}{2}} \tag{2}$$

The heliopause surface is obtained with $\eta = 1$. Distances are measured in units of the (spherical) termination shock distance R_{TS}. Together with a spherical termination shock one obtains the principal flow geometry shown in Fig. 1. As demonstrated in detail in [22, 23, 21]

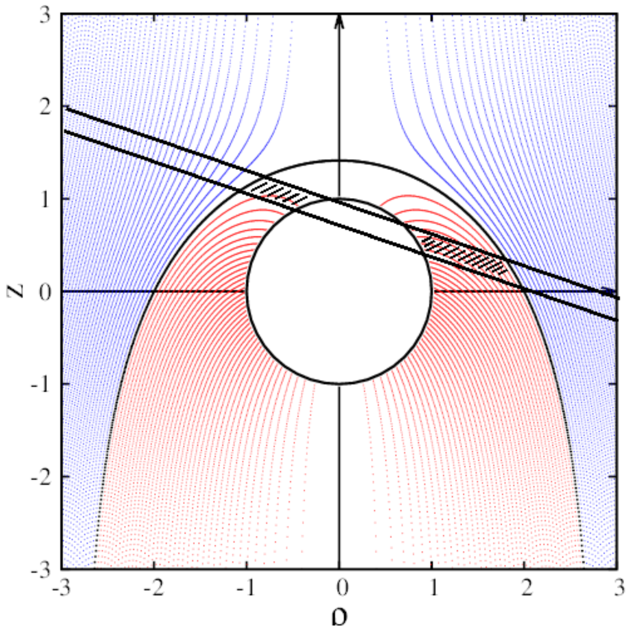

Figure 1. The analytical representation of the large-scale flow structure of the heliosphere and the local interstellar medium (LISM) accoding to Eqs.(1). The upper parabolically shaped thick black line marks the heliopause surface (given by Eq.(2) for $\eta = 1$), the lower one is the termination shock. The colors indicate the flow in the IHS (red) and OHS (blue). The region between the two parallel planes (indicated by the two straight lines, representing the front and rear of the H-wave, for details see text) that is shaded in black must be the source region of ENAs if they originate in the IHS.

via comparisons with numerical simulations and observations, this flow model is remarkably sufficient to principally test models against measurements. Hence, it can be used to test the so-called H-wave hypothesis, which was proposed and first discussed in [20].

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3. The H-wave hypothesis

The so-called H-wave model falls into the second group of models explaining the ENA ribbon in the IBEX-Hi all-sky maps with ENAs originating in the IHS. It is, however, the only one that makes a variation in the number density of neutral hydrogen atoms responsible for the increased ENA flux. The basic idea is to acknowledge the inhomogeneity of the local interstellar medium (LISM) also regarding its neutral hydrogen component. From various observations of the general ISM it is known that it is not only inhomogeneous on the large kpc- and pc-scales [28, 29, 30], but also on the sub-pc- down to the 10-100 AU-scales [31] and that this is not only valid for the plasma but also for the neutral component [32, 33]. As argued in [20], the coupling of the plasma and the neutral component (see, e.g., [34, 35, 36]) may lead to the formation of so-called H-waves, i.e. an enhancement in the number density of neutral hydrogen. The existence of such waves has also been predicted by [37]. Such H-wave signature must be expected to decouple from the plasma flow structures in the OHS [20] and to penetrate the heliopause as sketched in Fig. 1 with the two parallel lines indicating the leading and trailing edge of the density enhancement. The (in 3-D) ring-like intersection of such an H-wave with the IHS defines the source region of the ribbon ENAs, because the neutral density enhancement there directly implies a correspondingly enhanced ENA flux. This way the circularity of the ribbon is naturally explained [38].

3.1. Test 1: Geometry of the ribbon

The quantitative study of the H-wave scenario outlined above [21] demonstrated that the indicated ring-like intersection of neutral density enhancement and IHS must indeed be the source region of the ribbon ENAs if the latter are originating inside the heliosphere. The best fit to the observed ribbon in the all-sky flux maps, obtained from the simplified, analytically prescribed termination shock and heliopause that is possibly tilted with respect to the LISM inflow direction, is shown in Fig. 2 at the example of the differential ENA flux at 1.11 keV. The

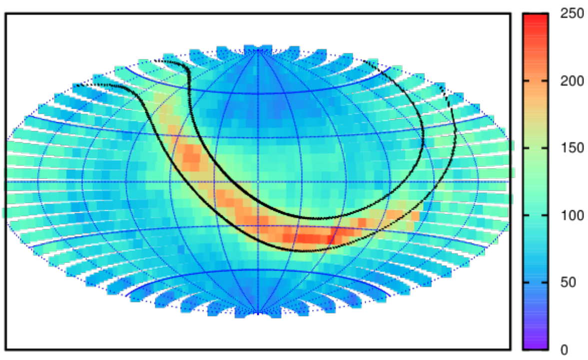

Figure 2. All-sky map of the differential ENA fluxes (ENAs/(cm^2 s sr keV) as observed by IBEX-Hi at 1.11 keV the simulated best-fit ribbon geometry, for details see text. Taken from [21].

fit parameters comprise the orientation of the H-wave normal $\vec{n}$ and its width in terms of the heliocentric distances $d_{1,2}$ of its leading and trailing edge, respectively. If the upwind direction is given by $\vec{e}_z = (0, 0, 1)$, the best fit normal (unit) vector is given by $\vec{n} = (-0.672, 0.485, 0.560)$ and the best fit H-wave width is $d_2 - d_1 = 0.4\ R_{TS} - 0.1\ R_{TS} = 0.3\ R_{TS}$. Evidently, the described method fits the ribbon excellently. That this also applies to the other IBEX-Hi energy bands up to 4.29 keV is discussed in [21] along with an analysis of the sensitivity of the fit to its parameters.

It is interesting to note that, independent from the H-wave hypothesis, this finding demonstrates that for geometrical reasons the source region of the ribbon ENAs must be the shaded area indicated in Fig. 1, if they are assumed to originate in the IHS.

3.2. Test 2: Orientiation of the undisturbed LISM magnetic field

Within the H-wave scenario it is clear that the normal vector $\vec{n}$ of the wavefront is not necessarily aligned to the undisturbed local interstellar magnetic field. Since, however, the orientation of the ribbon is undoubtedly related to the latter (see, e.g., [39, 1], another test of the H-wave hypothesis becomes possible. It is straightforward to compute the angle between the best fit normal vector and the upwind direction given by the z-axis as well as the corresponding ecliptic longitude λ_{ecl} and latitude δ_{ecl}. One finds [21] for the angle $\sphericalangle(\vec{n}, -\vec{u}_{ISM}) \approx (55 \pm 5)^{\text{o}}$, i.e. a value similar to the 49^{o} estimated by, e.g., [13]. While the values $\lambda_{ecl} \approx 205^{\text{o}}$ and $\delta_{ecl} \approx 35^{\text{o}}$ are slightly different from those discussed in the literature, these findings translate into the fact that the H-wave front is at least almost perpendicular to the undisturbed LISM magnetic field. This, in turn, is consistent with studies claiming indeed that a tilt of the phase front normal w.r.t. the field direction should be expected to be small [40, 41].

3.3. Test 3: Location in space

One reason for the persistence of two model groups to explain the IBEX ribbon is the fact that the spatial location of the ENAs constituting the associated enhanced fluxes has, as yet, not been identified. Only recently, a first attempt has been made to estimate the heliocentric distance d_{ribbon} of a ribbon element by determining its parallax [42]. While as such this represents a very worthwile enterprise that, in principle, has the potential to discriminate between the two model groups, the accuracy is, so far, still too low to do so in practice. These authors discussed in detail all major error or uncertainty sources and eventually found a value of $d_{ribbon} = 140^{+84}_{-38}$ AU, which obviously does neither favour the IHS- nor the OHS-origin of the ribbon ENAs.

The authors state further that they can neither confirm nor reject that the ribbon ENAs are created at different heliocentric distances depending on energy. It is, however, interesting to note that, if anything, their results would favour a decrease in heliocentric distance with increasing ENA energy (see their Table 1), which cannot be expected from the models of the first group claiming an OHS-origin of the ribbon ENAs, see, e.g. [15]. Evidently, one must hope for a significant increase in the accuracy of the parallax determination by either refining the analysis presented by [42] or by devising a different method to identify the source region of the ribbon ENAs.

Despite these positive and partially inconclusive tests of the H-wave hypothesis, the question whether such waves do exist in the interstellar medium remains to be answered. From a conceptual point of view it appears plausible that H-waves exist because (i) they could be generated at the nearest border of the local cloud the heliosphere is immersed in, i.e. in a distance of about 10000 AU [43] or (ii) they could be a result of turbulence cascading from larger to smaller scales (and corresponding coupling to the neutral component) as expected in view of the 'big power law in the sky' [44]. If the disturbances are first generated in the plasma component they can be transferred via change exchange coupling to the neutral component. While it has been demonstrated by [37] with an analytical study that such coupling indeed results in the generation of H-waves, more detailed and refined analyses still have to be made with numerical simulations in order to clarify the nature of disturbances in the neutral component of the LISM.

4. Proton velocity distribution in the inner heliosheath

Future tests must go beyond these mainly geometric considerations and comprise a computation of the differential fluxes of ENAs at different energies. A central ingredient for this is the knowledge of the proton source distribution in the IHS from which the ENAs are produced as a consequence of charge exchange. Assuming the principal form of the combined velocity distribution of thermal (solar wind) and suprathermal (pick-up) protons to be of κ-type (as done in [45] and [46]) and following the procedure used in [47], one can derive an ordinary differential equation for the variation of the κ-parameter along a given flow line:

$$\frac{d\kappa}{d\rho} = \frac{\kappa(\rho)(2\kappa(\rho)-3)u(\rho)}{3u_\rho(\rho)}\left[\frac{2}{3u}\frac{du}{d\rho} - \frac{10D_0(\rho)}{u(\rho)} + \frac{3n_H\sigma}{10\pi^{3/2}\kappa(\rho)}\right] \tag{3}$$

where D_0 denotes the velocity diffusion coefficient, n_H the neutral hydrogen density, and σ the charge exchange cross section. Typical values are $D_0 = 10^{-9}\text{s}^{-1}$ [48], $n_H = 0.1\text{cm}^{-3}$ [49], and $\sigma_{ex} = 10^{-15}\text{cm}^2$ [50]. The solution of this differential equation is shown along three different flowlines in the IHS ($\eta = 0.4, 0.65$ and 0.95 in Eq.(2). Fig. 3 illustrates that velocity diffusion

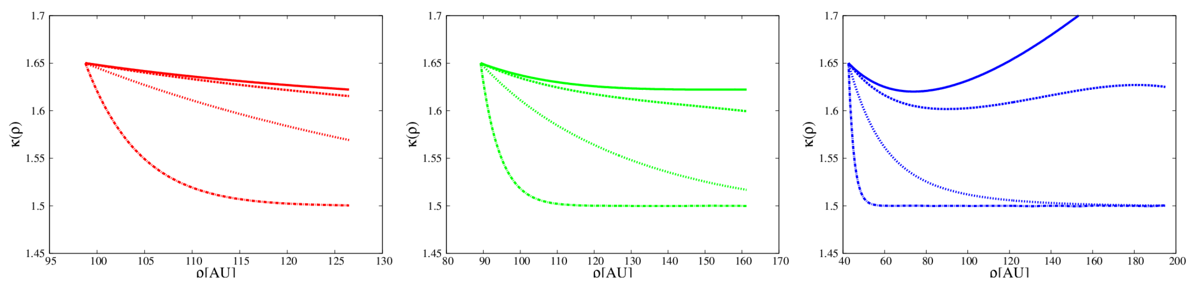

Figure 3. The variation of κ between the termination shock and the plane $z = 0$ along three flow lines given by Eq.(2) with $\eta = 0.4$ (left), 0.65 (middle) and 0.95 (right panel). In each panel the curves are computed from Eq.(3) for a velocity diffusion coefficient $D_0 = 0\ \text{s}^{-1}$ (solid line), 10^{-10}s^{-1} (dashed line), 10^{-9}s^{-1} (dotted line), and 10^{-8}s^{-1} (dash-dotted line).

overcompensates any increase of κ due to a loss of suprathermal protons via charge exchange. Given that the velocity diffusion coefficient is varied over two orders of magnitude this finding appears to be robust. Evidently, $1.62 < \kappa < 1.65$ for most regions in the upwind heliosphere ($z \geq 0$) for the case of vanishing diffusion. For the cases with $D_0 \neq 0$ one has $1.5 < \kappa < 1.65$ everywhere with a preference for the lower values. One the one hand this corroborates a value of $\kappa < 1.65$ in the upwind IHS as used earlier (e.g., [45]), on the other hand it clearly shows that the assumption of a constant κ should not be made.

5. Conclusions

In this brief report we have reviewed the H-wave hypothesis and discussed three tests, namely the resulting geometry of the ENA ribbon, the associated orientation of the local interstellar magnetic field, and the location of the ribbon ENA source region in space. With all tests we found the hypothesis to be consistent with the available data. A future test should consist in an analysis as to the existence of H-waves in the interstellar medium.

We continued with presenting an approximate solution of the combined thermal and suprathermal proton transport equation in the inner heliosheath. This solution, expressed as a κ-function, gives the range of κ-values to be expected, therewith confirming both that previsouly used values were of the right order and that the previously made asumption of a location-independent κ should not be made.

With such distribution functions of the seed population of the ENAs in the inner heliosheath, the next step of the quantitative analysis can be carried out, namely the computation of all-sky ENA flux maps that include the ribbon feature.

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References

[1] McComas D J, Allegrini F, Bzowski M, Dayeh M A, DeMajistre R, Funsten H O, Fuselier S A, Gruntman M, Janzen P H, Kubiak M A, Kucharek H, Möbius E, Reisenfeld D B, Schwadron N A, Sokół J M and Tokumaru M 2014 *Astrophys. J. Supp.* **213** 20
[2] Schwadron N A, Allegrini F, Bzowski M, Christian E R, Crew G B, Dayeh M, DeMajistre R, Frisch P, Funsten H O, Fuselier S A, Goodrich K, Gruntman M, Janzen P, Kucharek H, Livadiotis G, McComas D J, Moebius E, Prested C, Reisenfeld D, Reno M, Roelof E, Siegel J and Vanderspek R 2011 *Astrophys. J.* **731** 56
[3] McComas D J, Allegrini F, Bochsler P, Bzowski M, Collier M, Fahr H, Fichtner H, Frisch P, Funsten H O, Fuselier S A, Gloeckler G, Gruntman M, Izmodenov V, Knappenberger P, Lee M, Livi S, Mitchell D, Möbius E, Moore T, Pope S, Reisenfeld D, Roelof E, Scherrer J, Schwadron N, Tyler R, Wieser M, Witte M, Wurz P and Zank G 2009 *Space Sci. Rev.* **146** 11–33
[4] Grzedzielski S, Bzowski M, Czechowski A, Funsten H O, McComas D J and Schwadron N A 2010 *Astrophys. J.l* **715** L84–L87 (*Preprint* 1004.3917)
[5] Chalov S V, Alexashov D B, McComas D, Izmodenov V V, Malama Y G and Schwadron N 2010 *Astrophys. J.l* **716** L99–L102 (*Preprint* 1003.4826)
[6] Heerikhuisen J, Pogorelov N V, Zank G P, Crew G B, Frisch P C, Funsten H O, Janzen P H, McComas D J, Reisenfeld D B and Schwadron N A 2010 *Astrophys. J.l* **708** L126–L130
[7] Heerikhuisen J and Pogorelov N V 2011 *Astrophys. J.* **738** 29
[8] Strumik M, Ben-Jaffel L, Ratkiewicz R and Grygorczuk J 2011 *Astrophys. J.l* **741** L6
[9] Möbius E, Liu K, Funsten H, Gary S P and Winske D 2013 *Astrophys. J.* **766** 129
[10] Schwadron N A and McComas D J 2013 *Astrophys. J.* **764** 92
[11] Zirnstein E J, Heerikhuisen J, McComas D J and Schwadron N A 2013 *Astrophys. J.* **778** 112
[12] Burlaga L F, Ness N F, Florinski V and Heerikhuisen J 2014 *Astrophys. J.* **792** 134
[13] Heerikhuisen J, Zirnstein E J, Funsten H O, Pogorelov N V and Zank G P 2014 *Astrophys. J.* **784** 73
[14] Isenberg P A 2014 *Astrophys. J.* **787** 76 (*Preprint* 1404.2170)
[15] Zirnstein E J, Heerikhuisen J, Funsten H O, Livadiotis G, McComas D J and Pogorelov N V 2016 *Astrophys. J.l* **818** L18
[16] Krimigis S M, Mitchell D G, Roelof E C and Decker R B 2010 *American Institute of Physics Conference Series* (*American Institute of Physics Conference Series* vol 1302) ed Le Roux J, Zank G P, Coates A J and Florinski V pp 79–85
[17] Fahr H J, Siewert M, McComas D J and Schwadron N A 2011 *Astron. Astrophys.* **531** A77
[18] Kucharek H, Fuselier S A, Wurz P, Pogorelov N, Borovikov S, Lee M A, Moebius E, Reisenfeld D, Funsten H, Schwadron N and McComas D 2013 *Astrophys. J.* **776** 109
[19] Siewert M, Fahr H J, McComas D J and Schwadron N A 2013 *Astron. Astrophys.* **551** A58
[20] Fichtner H, Scherer K, Effenberger F, Zönnchen J, Schwadron N and McComas D J 2014 *Astron. Astrophys.* **561** A74
[21] Sylla A and Fichtner H 2015 *Astrophys. J.* **811** 150 (*Preprint* 1508.07815)
[22] Isenberg P A, Forbes T G and Möbius E 2015 *Astrophys. J.* **805** 153 (*Preprint* 1504.00585)
[23] Röken C, Kleimann J and Fichtner H 2015 *Astrophys. J.* **805** 173 (*Preprint* 1412.7199)
[24] Kleimann J, Röken C, Fichtner H and Heerikhuisen J 2016 *Astrophys. J.* **816** 29 (*Preprint* 1509.02699)
[25] Parker E N 1961 *Astrophys. J.* **134** 20
[26] Czechowski A, Fahr H J, Lay G and Hilchenbach M 2001 *Astron. Astrophys.* **379** 601–610
[27] Fahr H J and Siewert M 2015 *Astron. Astrophys.* **576** A100
[28] de Avillez M A and Breitschwerdt D (eds) 2004 *From Observations to Self-Consistent Modelling of the ISM in Galaxies. JENAM 2002 Workshop, Porto, Portugal, 3-5 September 2002. Reprinted from Astrophys. Space Sci. 289, Nos. 3-4, 2004. Kluwer Academic Publishers, Dordrecht*

[29] Hennebelle P and Audit E 2007 *SINS - Small Ionized and Neutral Structures in the Diffuse Interstellar Medium* (*Astronomical Society of the Pacific Conference Series* vol 365) ed M Haverkorn & W M Goss p 133 (*Preprint* arXiv:astro-ph/0701685)
[30] Breitschwerdt D, de Avillez M A, Fuchs B and Dettbarn C 2009 *Space Sci. Rev.* **143** 263–276
[31] Haverkorn M and Goss W M (eds) 2007 *SINS - Small Ionized and Neutral Structures in the Diffuse Interstellar Medium* (*Astronomical Society of the Pacific Conference Series* vol 365)
[32] Heiles C 1997 *Astrophys. J.* **481** 193
[33] Cho J and Lazarian A 2003 *Mon. Not. Roy. Astron. Soc.* **345** 325–339 (*Preprint* arXiv:astro-ph/0301062)
[34] Diver D A, Potts H E and Teodoro L F A 2006 *New Journal of Physics* **8** 265
[35] Shaikh D and Zank G P 2010 *Physics Letters A* **374** 4538–4542 (*Preprint* 1009.1859)
[36] Kellum M E and Shaikh D 2011 *Journal of Plasma Physics* **77** 577–588 (*Preprint* 1012.0940)
[37] Krasnobaev K V 1989 *Soviet Astronomy Letters* **15** 429
[38] Funsten H O, DeMajistre R, Frisch P C, Heerikhuisen J, Higdon D M, Janzen P, Larsen B A, Livadiotis G, McComas D J, Möbius E, Reese C S, Reisenfeld D B, Schwadron N A and Zirnstein E J 2013 *Astrophys. J.* **776** 30
[39] McComas D J, Lewis W S and Schwadron N A 2014 *Reviews of Geophysics* **52** 118–155
[40] Lerche I 1978 *Astrophys. Space Sci.* **57** 233–239
[41] Zaqarashvili T V, Khodachenko M L and Rucker H O 2011 *Astron. Astrophys.* **529** A82 (*Preprint* 1101.3913)
[42] Swaczyna P, Bzowski M, Christian E R, Funsten H O, McComas D J and Schwadron N A 2016 *Astrophys. J.* **823** 119 (*Preprint* 1603.09134)
[43] Redfield S and Linsky J L 2000 *Astrophys. J.* **534** 825–837
[44] Spangler S 2007 *American Astronomical Society Meeting Abstracts #210* (*Bulletin of the American Astronomical Society* vol 39) p 162
[45] Heerikhuisen J, Pogorelov N V, Florinski V, Zank G P and le Roux J A 2008 *Astrophys. J.* **682** 679–689 (*Preprint* 0803.2538)
[46] Zirnstein E J and McComas D J 2015 *Astrophys. J.* **815** 31
[47] Fahr H J, Fichtner H and Scherer K 2014 *Journal of Geophysical Research (Space Physics)* **119** 7998–8005
[48] Kallenbach R, Hilchenbach M, Chalov S V, Le Roux J A and Bamert K 2005 *Astron. Astrophys.* **439** 1–22
[49] Zank G P, Heerikhuisen J, Wood B E, Pogorelov N V, Zirnstein E and McComas D J 2013 *Astrophys. J.* **763** 20
[50] Lindsay B G and Stebbings R F 2005 *Journal of Geophysical Research (Space Physics)* **110** 12213–+