**Earth’s Magnetosphere Under Solar Wind Forcing**

The structure of magnetic field surrounding the Earth is continually changing in direction and strength by the driving from the solar wind plasma that flows over and into the Earth’s ionospheric plasma. Burst of strong solar wind plasma create magnetosphere storms and substorms that disrupt radio and GNSS [global satellite navigational system] communication and positioning systems.

C. J. Farrugia et al., J.G.R. 1993, vol. 98,A5 pp7657-767

Other well studied planets with strong magnetic field fields -particularly Jupiter and Saturn also have large complex plasma structures with similar features, however the structure of the Earth’s magnetosphere is known in much more detail due to the decades of space craft missions that have measured the plasma particle distributions and the magnetic field structures over the regions from where solar wind plasma dominates in the magnetic pause - or transition layer- into the magnetosphere where the dipolar magnetic field pressure dominates. The transition layers are complex and particularly important both for weather, defense and history of the life on the planet Earth.

The GEOTAIL spacecraft measured the hot high speed plasma in the plasma sheet arising from slow shock fronts driven by the solar plasma as reported in M. Hoshino et al. Adv.Space Res. Vol. 20 973-982,1997 that related the measured ratio of 2p/rho \*v^2 to that given by the slow shock theory.

The measured and theoretical temperature anisotropy and density jump correlated with theory.

While the dipole magnetic field of the Earth created by complex current structures in the core of the planet estimates of their structure give a strong field that explains that the field has reversed several times over the 4.5 billion years of the planet’s life. The source field is well approximated as a constant dipolar magnetic field structure with horizontal magnetic field lines in the solar equator. The latitude and longitude where the magnetic field lines are horizonal is defined as the magnetic equator. For example, Brazil in South America is near the magnetic equator as opposed to Canada and Norway where the field lines are nearly vertical. Plasma flows freely along the magnetic flux tubes that connect these regions from the southern to northern hemispheres. The plasma component with small pitch angle follows the field lines to the upper atmosphere producing intense ionization light creating the auroral borealis lights in Alaska and northern Canada.

A dipole magnetic field is the first approximation the planet’s magnetic that confines the particles as in the laboratory magnetic mirror machines described in the FusionPedia **Mirror Plasma Confinement**. The observations of the light emitted by hot magnetic ionospheric plasma particles ionizing the nitrogen and oxygen atoms in the atmosphere was first measured and explained by XXX in 190X. In the inner magnetosphere the magnetic field is described by the (B,L) parameters for the dipole magnetic field of strength B at the magnetic equator where the field line is crossing the magnetic is of strength B where crossing the magnetic equator where the vector B is horizontal. Below the is magnetic equator the field vector points upward and above the magnetic equator the vector points downward. Far north in Alaska and Canada the field is pointing downward at approximately 300 degrees from the vertical and at here the electrons following the field produce large ionization levels in the upper atmosphere seen as the Northern Lights from the recombination radiation of the ionized oxygen and nitrogen molecules in the upper atmosphere.

The ionospheric currents producing the Northern lights are first described by Birkeland proposed in 1908 in the book *The Norwegian Aurora Polaris Expedition 1902–1903*[[7]](https://en.wikipedia.org/wiki/Kristian_Birkeland?wprov=srpw1_16#cite_note-NAPE-7) that polar electric currents, today referred to as [auroral electrojets](https://en.wikipedia.org/wiki/Electrojet#Auroral_Electrojet). The currents systems are plasma currents that flow along geomagnetic field lines into and away from the polar region. Such field-aligned currents are known today as [Birkeland currents](https://en.wikipedia.org/wiki/Birkeland_currents" \o "Birkeland currents). Birkeland developed a diagram of a field-aligned currents in the book from his [terrella](https://en.wikipedia.org/wiki/Terrella) experimental system from the 1902–1903 expeditions.

Birkeland's vision of what are now known as [Birkeland currents](https://en.wikipedia.org/wiki/Birkeland_currents" \o "Birkeland currents) became the source of a controversy that continued for over half a century, because their existence could not be confirmed from ground-based measurements alone. His theory disputed by mainstream scientists. The eminent British [geophysicist](https://en.wikipedia.org/wiki/Geophysics) and [mathematician](https://en.wikipedia.org/wiki/Mathematician) [Sydney Chapman](https://en.wikipedia.org/wiki/Sydney_Chapman_(mathematician)) argued the mainstream view that currents could not cross the vacuum of space and therefore the currents had to be generated by the Earth. Birkeland's theory of the aurora continued to be dismissed by mainstream astrophysicists after his death in 1917. Finally, the famous Hannes Alfven recognized the physics and explained the origin and physics of the Birkeland currents that were validated by early space rocket data experiments in the high ionosphere plasmas.

**Magnetic Reconnection of the Solar Wind Plasma with Magnetic Field of the Planet Earth**

As described in Chapter 1-4 of ***Turbulent Transport in Magnetized Plasmas*** [W. Horton, 2nd Edition, 2018, ISBN 978-981-3225-88-6] plasmas in magnetic fields merge in complex dynamics where the self-consistent dynamics of the ions, electrons in the plasmas create electric currents that form the self-consistent magnetized plasmas we measure both in the space and astrophysical plasmas. From 190X the existence and measurements of the ionized molecules in the sun and in the upper region of the Earth’s atmosphere was recognized and measured. The dynamics is combination of that produced by the electric and magnetic fields form Maxwell’s equations and the motion of the charged particles [electrons relative to the ions or ionized atoms] that creates the electric currents in the gas.

In the 20th Century the combination of electrical engineering and computer technology give rise to the construction of compact spacecrafts that measure the planetary, solar and interstellar plasmas with precision. The recent examples are the Voyager I and Voyager II space craft that left Earth’s magnetosphere in 1976, travelled past Jupiter and Saturn in 1995 and returned the first data on the boundary plasma between the Sun’s plasma and the interstellar plasma in 2019. These spacecrafts are now in the plasma outside plasma produced by the Sun called the solar plasma.

Precision measurements of the magnetospheric plasmad are developed by both NASA and by the Military owing to their importance of weather and military defense measurements of the magnetospheric and ionospheric plasmas. The Naval Research Laboratory in Washington DC is an international leader in the analysis of space plasma physics.

An overview of the extensive international collaborations on research of the solar wind plasma that drives structures in the Earth’s magnetospheric plasmas creating

solar wind driven storms and substorms that disrupt the communication and navigational systems is given by ten authors in the

Journal of Geophysical Research 10.1002/2014/A019879 entitled “Structure of a reconnection layer poleward of the cusp: Extreme density asymmetry and a guide field” which starts with a figure showing measurements for plasma density, ion and electron temperatures, velocities and pressures with the simultaneous measured three components of the vector magnetic field taken from the WIND spacecraft during the magnetospheric storm on April 11, 1997. The storm was driven by a coronal mass ejection [ICME] from the Sun a day earlier.

The ejections of solar plasmas are a major cause of national security and weather changes on the Earth and monitored by ground based and satellite systems by nations around the Earth. A small fraction of the GNSS [Global Navigational Satelite System] data from GPS, GLONASS, Bedieu and Galilieo is shared to form the guidance signals for cars and aircraft guidance around the world.

The Voyager I spacecraft gave detailed measurements of the magnetosphere of our largest planet Jupiter showing a structure similar to that of the Earth’s magnetosphere but with a more complex plasma sphere due to the plasma emitted from a volcano on one of the four large planets discovered by Galileo with his telescope in XXXX [M. Kivelson and C. Russell (1995) *Introduction to Space Physics*] The planet Calisto has volcanoes emitting sulphur gas that is ionized form large regions of sulphur plasma that is used to study the dynamics of the huge Jovian magnetosphere along with the “Great Red Spot” dynamics in Jupiter’s surface plasma. The Jovian planets discovered and measured with some accuracy in location are Io, Europa, Ganymede and Callisto. The Great Red Spot – a large plasma vortex - and the Galilean moons are shown in Fig. XXX. Europa, the smallest of the four Galilean moons, is about the size of Earth's moon. Ganymede is the largest moon in the solar system. The image of Callisto is from the 1979 flyby of NASA's Voyager I spacecraft.

The dynamics of the electrons in the outer radiation becomes relativistic during periods of enhanced solar activity as described in M. L. Mays, W. Horton, J. Kozyra et al. Geophys. Res. Lett. 34, http://dx.doi.org./ 10.1029/2007GL029844 and L. R. Lyons, Y. Nishimura, E. Donovan and V. Angelopoulos, 2013, J. Geophys. Res. Space Phys 118:4080-4092.]. Enhanced periods of solar wind create relativistic electron populations that disrupt global communications systems.

**[Magnetic Reconnection and Response of the Earth’s Outer Radiations Belt](http://el.wiley.com/ls/click?upn=3P-2FFNDAGSso-2BACQqCJSxZQYXuyDFuSyQWVXTOVuATZfE2ZYhBvN14MKB0KVXOLGO8obGng7vSyli3t-2BN6pmypuehDHhLKKujEb7NGg1ivSDpY6GZZN5NStmHrvrt0DbrgKrwbAeHP8d0UlO1NUlIRDx8nGDA-2BO2zjs5VB4qXiObY1TG-2FYLFc-2Bw3Noa613Bm1wKs-2BI3fbHYCsr4GTa4crcEY4rZF3kGspD2eGRI2J8Vfs7mVH8bPl3HdepF8zy4UdfDUJMoMPiifN5x0-2BlPSaSOURX-2FHY0st87vklFIRW5VBGmfHIOrviZnxCnfSWAUFByP9xghcNspFl-2Bj9AZTUcSiMH3toYvuuJToP9nR9z47yp-2F9NfR5QtOV2Px-2Fr83zoSvjk3ig6CxDD0dot3PCg4lBnoD0CmUIm2hNrsOmA0lwWcfG2LmzWqi9xPmoZ3TLBGr7BL_WIPw-2BVdMIAhB0jCDFiHlvw3AeBJqRChiQ98goYBI-2FXTgvEXmeEooFUM5dDsB6XWDUdXti9oboqzBd7BTTF0wJoaVirSbz0zficE8tb0HKiqzDHnGnIc7QoSzJvaWIT-2BVEaQOxh45fGEF-2FiF52VpXI0tBFyuHSHB3wqaVvK1-2F3P9DHeRVHxvb8eqibn-2BOk9TCTstBztV9L51zncY5JFgAP4UPSGkoZmee-2FNlC7ATnxxTySYrRFbMj4SVJkeBrYTSwt-2BGd6e7Yzm9SRm9v-2FFmsz86wBz21XLXBhZbQ3wenrk8YLNIdpzN2-2FbZwKJIITP9S)**

##### **[Magnetic Reconnection](http://el.wiley.com/ls/click?upn=3P-2FFNDAGSso-2BACQqCJSxZQYXuyDFuSyQWVXTOVuATZfE2ZYhBvN14MKB0KVXOLGO8obGng7vSyli3t-2BN6pmypuehDHhLKKujEb7NGg1ivSDpY6GZZN5NStmHrvrt0DbrgKrwbAeHP8d0UlO1NUlIRDx8nGDA-2BO2zjs5VB4qXiObY1TG-2FYLFc-2Bw3Noa613Bm1wKs-2BI3fbHYCsr4GTa4crcEY4rZF3kGspD2eGRI2J8Vfs7mVH8bPl3HdepF8zy4UdfDUJMoMPiifN5x0-2BlPSaSOURX-2FHY0st87vklFIRW5VBGmfHIOrviZnxCnfSWAUFByP9xghcNspFl-2Bj9AZTUcSiMH3toYvuuJToP9nR9z47yp-2F9NfR5QtOV2Px-2Fr83zoSvjk3ig6CxDD0dot3PCg4lBnoD0CmUIm2hNrsOmA0lwWcfG2LmzWqi9xPmoZ3TLBGr7BL_WIPw-2BVdMIAhB0jCDFiHlvw3AeBJqRChiQ98goYBI-2FXTgvEXmeEooFUM5dDsB6XWDUdXti9oboqzBd7BTTF0wJoaVirSbz0zficE8tb0HKiqzDHnGnIc7QoSzJvaWIT-2BVEaQOxh45fGEF-2FiF52VpXI0tBFyuHSHB3wqaVvK1-2F3P9DHeRVHxvb8eqibn-2BOk9TCTstBztV9L51zncY5JFgAP4UPSGkoZmee-2FNlC7ATnxxTySYrRFbMj4SVJkeBrYTSwt-2BGd6e7Yzm9SRm9v-2FFmsz86wBz21XLXBhZbQ3wenrk8YLNIdpzN2-2FbZwKJIITP9S)** [Radial Response of Outer Radiation Belt Relativistic Electrons During Enhancement Events at Geostationary Orbit](http://el.wiley.com/ls/click?upn=3P-2FFNDAGSso-2BACQqCJSxZQYXuyDFuSyQWVXTOVuATZfE2ZYhBvN14MKB0KVXOLGO8obGng7vSyli3t-2BN6pmypuehDHhLKKujEb7NGg1ivSDpY6GZZN5NStmHrvrt0DbrgKrwbAeHP8d0UlO1NUlIRDx8nGDA-2BO2zjs5VB4qXiObY1TG-2FYLFc-2Bw3Noa613Bm1wKs-2BI3fbHYCsr4GTa4crcEY4rZF3kGspD2eGRI2J8Vfs7mVH8bPl3HdepF8zy4UdfDUJMoMPiifN5x0-2BlPSaSOURX-2FHY0st87vklFIRW5VBGmfHIOrviZnxCnfSWAUFByP9xghcNspFl-2Bj9AZTUcSiMH3toYvuuJToP9nR9z47yp-2F9NfR5QtOV2Px-2Fr83zoSvjk3ig6CxDD0dot3PCg4lBnoD0CmUIm2hNrsOmA0lwWcfG2LmzWqi9xPmoZ3TLBGr7BL_WIPw-2BVdMIAhB0jCDFiHlvw3AeBJqRChiQ98goYBI-2FXTgvEXmeEooFUM5dDsB6XWDUdXti9oboqzBd7BTTF0wJoaVirSbz0zficE8tb0HKiqzDHnGnIc7QoSzJvaWIT-2BVEaQOxh45fGEF-2FiF52VpXI0tBFyuHSHB3wqaVvK1-2F3P9DHeRVHxvb8eqibn-2BOk9TCTstBztV9L51zncY5JFgAP4UPSGkoZmee-2FNlC7ATnxxTySYrRFbMj4SVJkeBrYTSwt-2BGd6e7Yzm9SRm9v-2FFmsz86wBz21XLXBhZbQ3wenrk8YLNIdpzN2-2FbZwKJIITP9S)

**V. A. Pinto, J. Bortnik, P. S. Moya, L. R. Lyons, D. G. Sibeck, Shrikanth G. Kanekal, Harlan E. Spence, Daniel N. Baker e2019JA027660**.

During the periods of enhanced solar plasma activity, the Earth’s magnetosphere has traps relativistic electrons and this produces strong disruptions of the global navigational systems signals. The plasma regions of the geostationary orbit are characterized by plasma enhancements at GEO generally penetrate to *L*=5.0 but at lower *L* they may respond differently and even be seen as depletions. Geomagnetic indices, especially *AE* and *D*st are used to predict and determine the lowest *L‐*shell L= 5R\_E show plasma enhancements and depletions.

**Spatial distribution of the eddy diffusion coefficients in the plasma sheet during quiet time and substorms from THEMIS satellite data**

The **THEMIS satellite** performed turbulent important analysis of the formation of quasi‐stable plasma sheet configurations in the magnetosphere. The turbulence provides a self‐consistent the dynamics of the Earth’s magnetosphere that includes the plasma sheet stability. The turbulence is important for an understanding of the location of an isolated substorm expansion phase onset. The level of turbulence has been evaluated by calculating the eddy diffusion coefficients using the Time History of Events and Macroscale Interactions from Substorms satellite data. It was found that the value of the eddy diffusion coefficients may vary by 3 orders of magnitude, generally ranging from 103 to 106 km2/s, increasing with the distance from the Earth. The area of low eddy diffusion coefficients, less than 104 km2/s, is situated at distances below 12 RE in the tail where there is a transition region between the dipole and the tail‐like geomagnetic field configuration. This region is consistent with the location of isolated substorms mapping the first auroral arc brightening situated at the equatorial edge of the auroral oval into the magnetosphere. [ Stepanova, M., V. Pinto, J. A. Valdivia, and E. E. Antonova (2011), Spatial distribution of the eddy diffusion coefficients in the plasma sheet during quiet time and substorms from THEMIS satellite data, J. Geophys. Res., 116, A00I24, doi:10.1029/2010JA015887. **[**M. Stepanova,1 V. Pinto,2,3 J. A. Valdivia,2 and E. E. Antonova4,5 [JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, A00I24, doi:10.1029/2010JA015887, 2011 ]

The data shows that plasmas can demonstrate very complex behavior that includes multiscale dynamics, emergence and self-organization, phase transitions, and turbulence with spatiotemporal chaos.. [Lu, 1995; Carreras et al., 1996; Valdivia et al., 1996, 2003, 2005, 2006; Biskamp, 2000; Klimas et al., 2000, 2010; Uritsky et al., 2007].

The magnetosphere is formed as a result of the interaction between the solar wind supersonic and super‐Alfvenic turbulent flow and the geomagnetic field. This interaction creates plasma turbulence in various regions of the magnetosphere, and in particular in its tail. There is a significant difference between a fluid turbulent wake behind an ordinary obstacle and the geomagnetic tail. The cross-section radius of the ordinary wake is close to that of the obstacle, while the magnetotail plasma separates into the plasma sheet and the plasma tail lobes. A number of studies have shown that turbulent processes in the plasma sheet are important for the understanding of this dynamics [Antonova, 1985; Angelopoulos et al., 1992, 1993; Borovsky et al., 1997; Ohtani et al., 1998]. As evidences of turbulence in the plasma sheet, it is possible to mention the “sky images” of near‐Earth space plasma, showing the presence of mul- tiple structures moving with different, and sometimes very large, velocities [Chamberlain, 1961]; or the presence of strong fluctuations in the electric fields at the auroral field lines measured by Viking, Freja, Fast, and Interkosmos‐ Bulgaria‐1300 satellites [Maynard et al., 1982; Mozer et al., 1980; Weimer et al., 1985; Stepanova et al., 2003a]. A clear manifestation of the existence of low‐frequency magnet-spheric turbulence was also obtained through analysis of fluctuations of geomagnetic indices [Takalo et al., 1993; Consolini and De Michelis, 1998; Uritsky and Pudovkin, 1998; Hnat et al., 2002; Stepanova et al., 2003b, 2005a; Pulkkinen et al., 2006; Wanliss and Uritsky, 2010], auroral absorption [Stepanova et al., 2005b, 2006], and Polar UVI images [Uritsky et al., 2008]. Measurements of the particle fluxes inside the plasma sheet allowed to study the fluctuations in the plasma bulk velocity and show that these fluctuations exceed significantly their average values [see Baumjohann et al., 1990; Angelopoulos et al., 1992, 1993, 1996, 1999; Borovsky et al., 1997, 1998; Borovsky and Funsten, 2003a, 2003b; Borovsky and Gary, 2009; Ovchinnikov et al., 2000; Troshichev et al., 2002; Stepanova et al., 2005c, 2009]. Despite differences in time resolution, the behavior of different components of the bulk velocity fluctuations is very similar, except for the bursty bulk flow events (BBFs), which produce asymmetry in the probability density function of the X and Y components of the inner plasma sheet flows in the GSE/GSM coordinate system. According to Baumjohann et al. [1990], Angelopoulos et al. [1992, 1993, 1996, 1999], G. Paschmann et al. Space Science Reviews, 118 2005, and N. Borodkova [2002], when BBFs are removed from the plasma sheet observational database, the plasma flow has an average convection that is small and a variance that is many times larger than its average.

The existence of this turbulence provides a self‐ consistent approach to study the dynamics of the Earth’s magnetosphere, including the plasma sheet stability and the location of the expansion onset of isolated substorms [Antonova and Ovchinnikov, 1996, 1999; Antonova et al., 1998; Stepanova et al., 2002, 2005c, 2009]. For example, on the average, the magnitude of the plasma bulk velocity in the magnetosphere of the Earth is smaller than the Alfven and sound speeds. Thus, the condition of magnetostatic equilibrium (forces connected to the existence of plasma pressure gradients are compensated by the Ampere’s force) is generally fulfilled. Along this line, Antonova and Ovchinnikov [1996, 1999, 2001] proposed that a stable turbulent plasma sheet can be formed when the regular plasma transport, produced by the dawn‐dusk electric field across the plasma sheet, is compensated by the eddy diffusion turbulent transport across it. They consider that the plasma particle flux is equal to S = nhVi − Drn, where n is the average of the turbulent plasma particle density fluctuation, hVi is the averaged bulk velocity, and, D is an eddy diffusion coefficient. When the turbulent fluctuations act to expand the plasma sheet, the large‐scale electrostatic dawn‐dusk electric field tries to compress the sheet. When the expansion and compression compensate each other, a stationary structure is formed. This assumption allows to predict the order of magnitude of the eddy diffusion coefficient in the Z direction 105 km2/s, that is necessary to reproduce the observed plasma sheet thickness. This value agrees with the estimated eddy diffusion coefficients, obtained from measurements by the ISEE‐2, Interball‐Tail, and GEOTAIL satellites [Borovsky et al., 1997, 1998; Borovsky and Funsten, 2003b; Ovchinnikov et al., 2000; Troshichev et al., 2002; Stepanova et al., 2005c, 2009]. Furthermore, the eddy diffusion transport in the plasma sheet is affected by the location inside the plasma sheet, the geomagnetic activity, and the solar wind parameters [Ovchinnikov et al., 2000; Neagu et al., 2002, 2005; Stepanova et al., 2005c, 2009; Nagata et al., 2008; Wang et al., 2010].

The nature of the observed turbulence is still not clear since there is a number of physical processes leading to the turbulence generation which depend on both the spatially and temporal scales. Antonova et al. [1998], Luizar et al. [2000], and Antonova [2002] suggested that plasma pressure gradients are the most probable candidates for the generation of large‐ and medium‐scale harmonics of the magnetospheric turbulence. There are also indications that the level of magnetic turbulence in the magnetotail correlates with the level of the velocity perturbations and particle beams which dramatically increase with the flow velocity. Therefore, shear flows and particle beams are also premiere candidates for the generation of turbulence [Bauer et al., 1995; Vörös et al., 2004].

Eventhough the plasma sheet appears to be a dynamic and turbulent region [Borovsky et al., 1997; Ohtani et al., 1998], the substorm cycle seems coherent and repeatable with identifiable distinct phases [Baker et al., 1999] and predictable geomagnetic indices [Vassiliadis et al., 1995; Valdivia et al., 1996, 1999]. It has been suggested that the resolution to these seemingly contradicting observations should be through the understanding of the process of self organization in plasmas [Chang, 1999; Uritsky and Pudovkin, 1998; Valdivia et al., 2005, 2006; Uritsky et al., 2009a]. The possibility of an inverse turbulent cascade has been discussed by Uritsky et al. [2001] and Rosa et al. [1998]. Furthermore, the interaction between different har- monics of the magnetospheric turbulence is not well explored. A number of works indicate that the turbulence in the plasma sheet has an intermittent character [Angelopoulos et al., 1999; Consolini and De Michelis, 1998; Stepanova et al., 2003b, 2006; Arancibia Riveros et al., 2008]. A very interesting approach to explain the processes leading to the formation of the spectrum of magnetospheric turbulence, including the self‐consistent influence of geomagnetic sub- storms and storms, is the concept of the self‐organized criticality [Chang, 1999; Uritsky and Pudovkin, 1998; Klimas et al., 2000; Valdivia et al., 2003, 2005, 2006; Uritsky et al., 2007, 2009b].

The THEMIS satellite data gives the Time History of Events and Macroscale Interactions during Substorms for the different phases of isolated magneto- spheric substorms.

The plasma instrument data Analysis THEMIS was acquired in the plasma sheet. The time intervals were selectef for the moments of the ion distribution functions obtained from the onboard moments calculations of the Electrostatic Analyzer (ESA) in the energy range from 25 eV to 25 KeV and Solid State Telescopes in the energy range from 25 keV to 6 MeV [McFadden et al., 2008; Angelopoulos, 2008]. The geomagnetic field measurements were provided by the fluxgate magnetometer (FGM) [Auster et al., 2008], which were used for the calculation of the plasma b parameter. In order to compare the previous results of Stepanova et al. [2009], using the Interball‐Tail satellite, the selected intervals were for plamas with number density n ≥ 0.1 cm−3, and ion temperature T ≥ 1 keV. The satellite Z coordinate is between −8 RE and 8 RE, with b ≥ 1, to ensure that the satellite is located in the plasma sheet. The X and Y coordinate of the satellites are shown in Figure 3.

Figure1showsanexampleofthedatafromTHEMIS C satellite on 26 February 2008. It can be seen, that the satellite not always was located inside the plasma sheet, and the combination of criteria n ≥ 0.1 cm−3 (not shown in Figure 1), T ≥ 1 keV, and b ≥ 1 is sufficiently robust to ensure the location of the satellite inside the plasma sheet Figure 2.

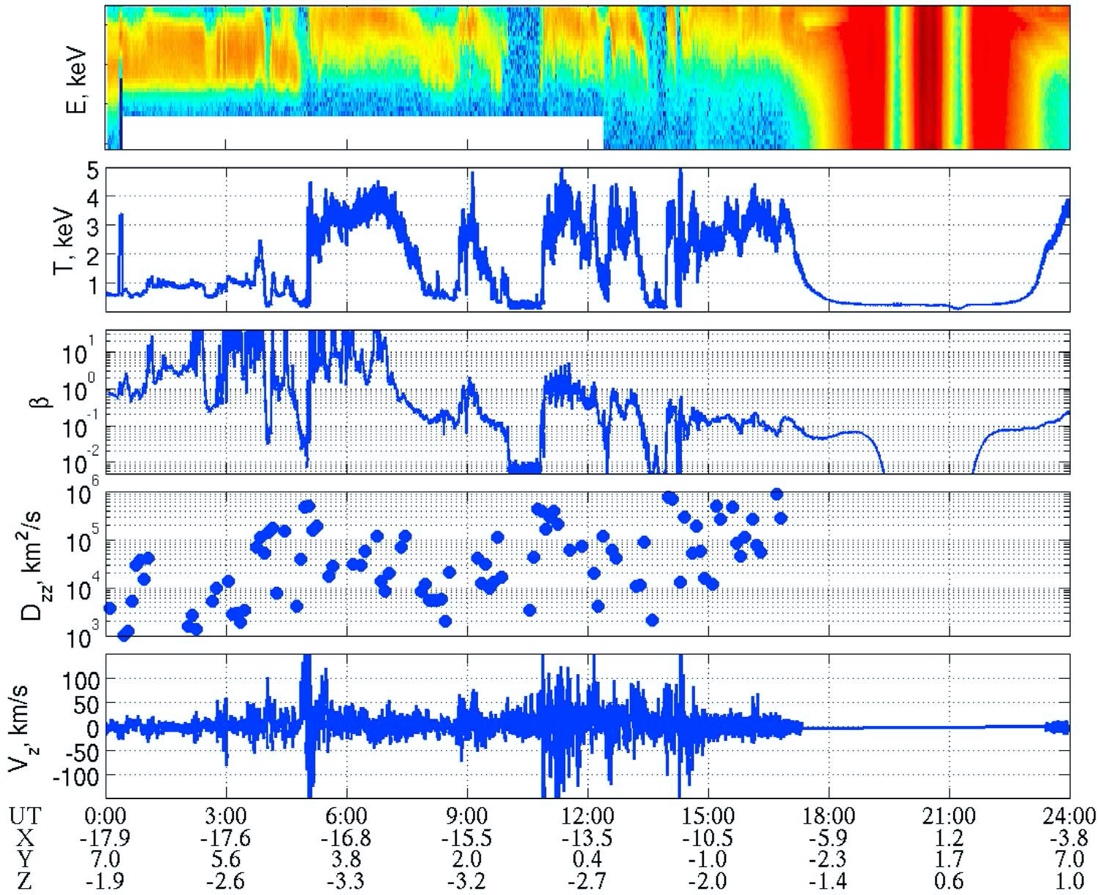


Figure 1. From top to bottom: (a) Ion spectrogram, (b) ion temperature, (c) plasma b parameter, (d) eddy diffusion coefficient, and (e) Z component of the bulk velocity and corresponding eddy diffusion coefficient obtained from the onboard moments of the ion distribution function measured by the THEMIS C on 26 February 2008.

The turbulent transport is inferred from the eddy diffusion coefficient tensor D required to is the describe the observed of the plasma transport produced by the turbulent convection vortexes in the diffusion approximation. This D tensor is very important for the understanding of the plasma sheet stability through the relation S = nhVi − Drn.

From the THEMIS data we can construct three components of the bulk velocity Va(i) in the GSM coordinate system with a time resolution of 3 seconds according to the probe spin time. If we take two of such components, for example a and b, the autocorrelation function was calculated.

The data was separated into 12 min intervals, that contain N = 240 bulk velocity data points. Adjacent intervals overlap for half of their length (6 min), and we use the center of the interval to mark the time. The autocorrelation time (tab) was determined as the best fit to the natural logarithm of the autocorrelation function by the linear expression y = 1 − ax, using only one parameter of fitting. Figure 2 shows an example of the bulk velocity Vz and the corresponding autocorrelation function with the respective fit. Three methods were used to estimate the autocorrelation time. In the first method finds the value t0 at which the logarithm of the autocorrelation function goes through zero. The second method uses the value tmin where the autocorrelation function has its first minimum and fits the value of tab using all the points between 0 ≤ t ≤ tmin. In the third method, uses the value te where the autocorrelation function goes below e−1 and fits tab using the points between 0 ≤ t ≤ te. With these three values of tab an average value of tab is derived as shown in Fig.2.

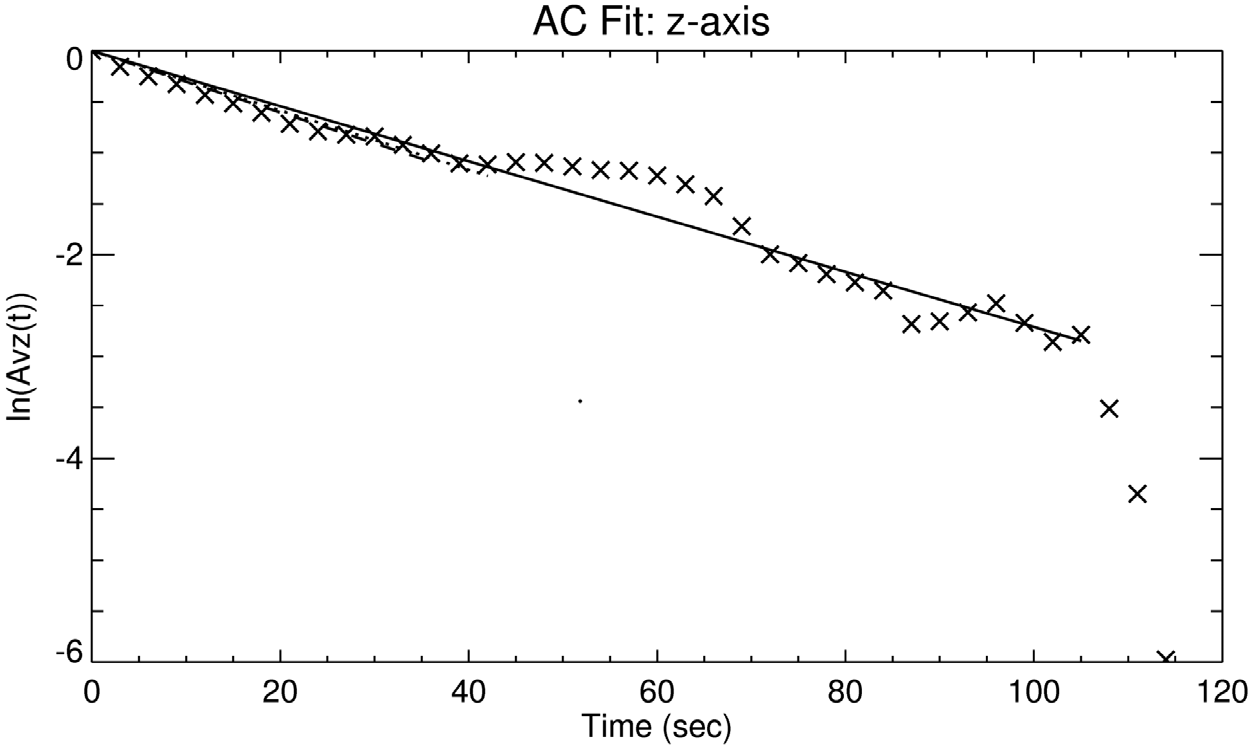


Figure 2. The autocorrelation function will all three fits, obtained from the THEMIS C satellite data on 26 February 2008 at 0509 UT.

Similarly, the mean square (rms) speed during the chosen time interval is determined from the value of the slope of the AL index was s ≥ 1/2 nT/min for 5 min with respect to the middle point of the interval, and s > 0 for 20 min with respect to the middle point of the interval. In this study the authors could not distinguish the data corresponding to the growth phase, as it was difficult to establish a clear criterion for automatic data extraction. To analyze the spatial distribution of the eddy diffusion coefficients the X‐Y GSM plane was partitioned into 30 overlapping bins between 6 and 30 RE into the tail, and between −p/4 and p/4, having midnight as 0, in the azimuthal direction. Each bin has an extension of 6 RE in the radial direction and p/12 in the azimuthal direction. Each next bin overlaps with the previous one for half step size (3 RE and p/24). This was done to improve the statistics so that each bin has at least 10 measurements of the eddy diffusion coefficients, which permits a smooth final distribution. The number of eddy diffusion coefficients measurements found in each bin is shown in Figure 3d, for each of the three different phases of isolated substorms.

Figure 3 shows the spatial distribution of diagonal terms of the eddy diffusion coefficient tensor in GSM coordinate system during the three different phases of isolated substorms considered in the analysis. While the values of the coefficients vary significantly, the analysis shows that on average all the diagonal terms of the eddy diffusion coef- ficient tensor increase with distance in the tail under all geomagnetic conditions. Furthermore, we have in general Dxx > Dyy, Dzz, as can be seen by comparing Figures 3 (left), 3 (middle), and 3 (right), as the eddy diffusion in X direction could be affected by the propagation of the bursty bulk flows (BBFs) studied by Baumjohann et al. [1990] and Angelopoulos et al. [1992]. Let us note that the values of the eddy diffusion coefficients obtained here are similar to the typically values reported for the plasma sheet. Finally, the eddy diffusion coefficient is obtained from

[14] Let us note that following this procedure makes it possible to estimate all components of the eddy diffusion coefficient tensor in the GSM basis, but for the purpose of the present manuscript we will only analyze the diagonal terms Dxx, Dyy and Dzz.

[15] With the three values for t, we can also estimate a deviation st, defined by half the difference between their minimum and maximum values. If this deviation is larger than 50% of the average value of t, we do not consider the interval in our analysis. It is important to mention that we also eliminate from the analysis the intervals that have small autocorrelation time (t < 10 s) and large autocorrelation time (t > 300 s). Exclusion large autocorrelation times partially removes the coherent flows.

[16] To determine whether the eddy diffusion coefficient is taken during the quiet time, expansion, or recovery phase of the substorm, we perform an analysis of the 1 min resolution Auroral Low (AL) index. The interval was considered as quiet when AL ≥ −100 nT and the absolute value of the slope s of the AL index was ∣s∣ ≤ 1/2 nT/min for 40 min before and after the middle of the interval. The interval was con- sidered as expansion when AL < −100 nT and the value of the slope of the AL index was s ≤ −1/2 nT/min for 5 min with respect to the middle point of the interval, and s < 0 for 20 min with respect to the middle point of the interval. The interval was considered as recovery when AL < −100 nT and Vrms; 1⁄4 N ð4Þ ð5Þ V2 ( rms; D1⁄4 2 :

Figure 3. Estimations of the spatial profile of diagonal terms of the eddy diffusion coefficients ((a) Dxx, (b) Dyy, and (c) Dzz) during the three different phases of isolated substorms considered in the analysis: (left) quiet phase, (middle) expansion phase, and (right) recovery phase. (d) The number of eddy diffusion measurements N in each bin for the three different phases of isolated substorms is also given. The color bar is used for D and N values.

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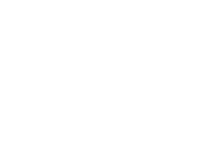
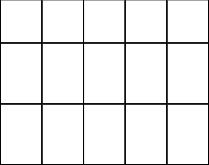


Figure 4.

Borovsky et al., 1998; Borovsky and Funsten, 2003b; Ovchinnikov et al., 2000; Troshichev et al., 2002; Stepanova et al., 2005c, 2009].

[19] Figure 4 shows the variation of eddy diffusion coef- ficient with the distance from the Earth, obtained by aver- aging the bins showed in Figure 3 by the angle. We can see that in general all the diagonal components of the eddy diffusion coefficient tensor tend to increase with distance from the Earth, especially during the expansion and recovery phases of substorms. There seem to be a saturation at around 10–15 RE, which could be related to the change from dipole to tail field. Unfortunately, the THEMIS mission does not account for a satellite at distances larger than 30 RE, so that we can only assume that this saturation effect continues, but we cannot be certain.

[20] We note that during substorms all three diagonal components, DXX, DYY, and DZZ, experience a significant increase with respect to the quiet times. There is a local maximum at a distance of ∼22 RE, that deserves further study.

[21] There is a clear dawn‐dusk asymmetry in all three diagonal elements of D, as can be seen in Figure 3. This effect occurs for all phases, but it is more significant during the recovery phase. It is also interesting to note that at around X = −20 RE and Y = −10 RE there is a local decrease in all three diagonal components, which may be related to the low statistics seen in Figure 3d.

3. Conclusions

Analysis of bulk velocity fluctuations obtained from THEMIS satellite mission allowed the derivation of the spatial distribution of the values of eddy diffusion coefficients for different phases of geomagnetic substorms and during quiet time inside the plasma sheet for all components of the bulk velocity. Obtained Dyy and Dzz distributions are similar to ones reported by Stepanova et al. [2009] using the Interball‐ Tail data. Nevertheless, better sampling of the bulk velocity allowed to detect new features in the behavior and distribution of the eddy diffusion coefficients and, unlike the Interball‐Tail satellite, to study the eddy diffusion in the X direction. The THEMIS data allowed the identification of quiet time intervals and the corresponding the expansion and recovery phases of the substorms. Eddy diffusion coefficients obtained for quiet geomagnetic conditions are close to those obtained by Nagata et al. [2008] and Wang et al. [2010].

The research showed that the values of eddy diffusion coefficients vary significantly, increasing on average in the tailward direction, especially during disturbed geomagnetic conditions. Furthermore, the values of the diagonal terms of the eddy diffusion coefficient tensor seem to saturate for large values of −X. This variation can reflect the transition from the region where the presence of the dipole geomagnetic field is still relevant, to the region where the geomagnetic field has a pure tail configuration.

The values of the eddy diffusion coefficients in Z direction were similar to those predicted by Antonova and Ovchinnikov [1996, 1999, 2001]. According to this research, a compact and comparatively stable turbulent plasma sheet can be formed when the plasma Variation of the eddy diffusion coefficients for (a) quiet, (b) expansion, and (c) recovery time intervals. DXX (black circles), DYY (white squares), and DZZ (black diamonds) are given.

Transport, produced by the dawn‐dusk electric field across the plasma sheet, is compensated by the eddy diffusion turbulent transport. When the turbulent fluctuations act to expand the plasma sheet, the large‐scale electrostatic dawn‐dusk electric field counteracts to compress the plasma, similarly to the case of the laboratory plasma pinch which is compressed by the induction electric field. When the expansion and compression compensate each other, a stationary structure is formed.

[25] It is necessary to stress that the existence of turbulence in the Earth’s magnetosphere is quite natural, taking into consideration that the solar wind plasma flowing around the Earth has high fluid and magnetic Reynolds numbers. In such a case a turbulent wake is expected to be formed.

[26] The increase in the values of diffusion coefficients with the distance in the tailward direction also can help to explain why the substorm onset takes place deeply inside the magnetosphere, as confirmed by many authors [see, e.g., Samson et al., 1992a, 1992b; Frank and Sigwarth, 2000; Lyons et al., 2002; Stepanova et al., 2002; Yahnin et al., 2002; Dubyagin et al., 2003; Antonova et al., 2009], because only the region which was stable before the onset of the substorm expansion phase can become unstable.

[27] There is a broad spectrum of plasma instabilities which could lead to such a substorm development (see, for example, the discussion by Stepanova et al. [2002, 2004] and Lui et al. [2008] and Antonova [2004] for a review).

[28] Nevertheless, the interplay between the turbulent processes in the plasma sheet and the geomagnetic sub- storms is not clear. It is necessary to concentrate a signifi- cant effort in understanding the processes involved for different time and space scales.

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The solar wind velocity increases from the sun toward the heliosphere as given by the isothermal expansion maintained by the rapid electron thermal transport. The speed and Mach numbers are roughly (i) at the Earth 400 km/s with Ms = 4, and (ii) at Jupiter 800 km/s with Ms = 8. Jupiter's magnetic moment MJ = 2 × 104 ME with Rmp ⋍ 45 RJ = 3 × 106/km where RJ = 7.1 × 104 km. The Earth's magnetic moment is ME = 8 × 1015 T.m3. Jupiter has a high level of relativistic electrons (flux > 106 cm-2 s-1) up to 20 MeV in energy. There is strong decimeter wavelength synchrotron radiation from relativistic electrons in the magnetosphere of Jupiter (Dessler, 1983).

A. J. Dessler, *Phys. Jovian Magnetosphere*, (A83-26611 10-91) Cambridge and New York, Cambridge University Press, 1983, p. 498-504, <https://ui.adsabs.harvard.edu/abs/1983phjm.book..498D/abstract>

Mildly supersonic Ms = u/cs ~ 1.4-5 plasma winds are common place in astrophysics and space physics. The winds may be associated with accretion to a central star. Winds occur in the precursor phase to the Type Ia supernova (SNIa) where plasma is pulled into the magnetic white dwarf (WD) from the companion star. Plasma winds are intercepted by neutron stars (NS). After stars ignite, the stellar wind outflow creates bow shocks at the magnetic planets and at the termination of the stellar outflow where the thermal pressure jumps to match that of the interstellar plasma gas. The heliopause is at 110-180 AU and Voyager 1 and Voyager 2 observed the accelerated particles when passing through the associated shock fronts.

**Exploring the Solar System with Voyager 1 and Voyager 2**

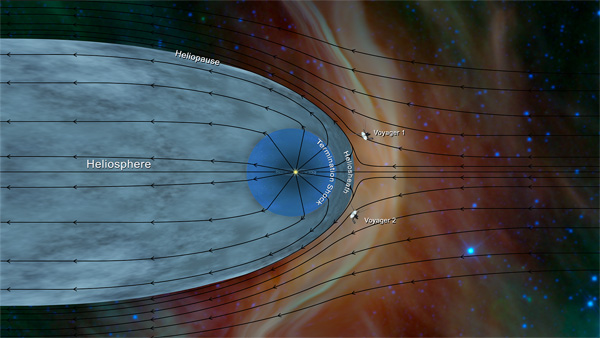
Voyager 2 crossed into interstellar space in 2019. Five teams of astronomers have analyzed the plasma data measured in the during the crossing of the interstellar boundary of the outer solar system.

Four decades after its launch into the outer solar system, Voyager 2 crossed the boundary that separates the solar plasma from the plasma that domain flows between the stars. The crossing on November 5, 2018 happened six years after that of the speedier Voyager 1.

Voyager 1 returned a surprisingly messy view of solar system outer boundary. In fact, astronomers had a hard time figuring out when the spacecraft had actually made the crossing. The Voyager 2 crossing was much sharper and with accurate measurements of the plasma density and temperature profile across the boundary layer. A dedicated issue of [*Nature Astronomy*](https://www.nature.com/articles/s41550-019-0928-3) describes the plasma variation measured during the crossing of the solar system boundary.

**Far from the Sun**

One could argue that neither Voyager has really left the solar system. For example, the Sun’s gravity holds the hypothesized shell of icy objects known as the Oort Cloud in orbit at a distance of some 100,000 astronomical units (a.u., the average distance between Earth and the Sun) — far beyond the Voyagers. What the two spacecraft have left behind, however, is the *heliosphere*, the cavity around the Sun blown out by the solar wind as described in this figure.



This illustration shows the position of NASA's Voyager 1 and Voyager 2 probes outside of the heliosphere. Voyager 1 crossed the heliopause, or the edge of the heliosphere, in August 2012. Heading in a different direction, Voyager 2 crossed another part of the heliopause in November 2018. The black lines mark the direction of plasma flow both inside and outside the heliopause. Solar plasma flows in a different direction than the interstellar plasma (NASA/JPL-Caltech).

Even though the Sun is pouring out charged particles into the heliospheric plasma bubble, the density of those particles decreases as the square of their distance from the Sun. By the edge of the heliosphere, matter has become incredibly sparse, a mere 0.002 electrons per cubic centimeter, as Donald Gurnett and William Kurth (both at University of Iowa) report in their analysis of Voyager 2 data. These particles have not lost their energy and remain very hot.

The gas and dust between the stars, on the other hand, is cold and dense. The particles of the interstellar medium, and the magnetic fields they carry, sweep around the heliosphere like ocean waves around a boat. The boundary between the two, known as the heliopause, is by its nature unstable. It “breathes,” expanding when the Sun is more magnetically active and shrinking when the Sun goes quiet.

Wherever the boundary is in the solar cycle the boundary is sharp marked by the same jumps in particle density and a drop in plasma temperature. The two Voyagers measured these transitions in detail as they traveled farther and farther from the Sun. Figure below describes the geometry and antennas on the Voyagers.



Fig. Caption Description of the Voyager spacecraft design and antennas for plasma measurements and the transmission of the plasma data to the Earth. (NASA/JPL-Caltech).

The Voyagers were launched a few weeks apart in 1977 for a grand tour of the outer solar system. Voyager 1 traveled faster and reached the heliopause first, speeding through the boundary in the northern hemisphere. However, some of its plasma instrument failed in 1980, so scientists had to analyze data from its other instruments to get readings on what particles in its vicinity were doing. While Voyager 1 reached the edge of the solar bubble on August 25, 2012, scientists did not fully realize this until after the crossing into the interstellar plasma and the crossing of Voyager 2 crossing in 2019 whose instruments gave more accurate data.

What made the Voyager 1 data confusing was that scientists had expected the direction of the magnetic field to change abruptly as Voyager 1 traversed from the solar to interstellar plasma. But Voyager 1 measured no clear change. Was it simply a coincidence that the magnetic field from inside the bubble, which comes from the Sun, had lined up just right with the one from outside the bubble, which comes from the stars?

### Voyager 2 data of the Heliopause Crossing

Like Voyager 1, Voyager 2 crossed the “nose” of the heliosphere — that is, into the flow of interstellar plasma, though Voyager 2 passed through the southern hemisphere. But unlike Voyager 1, Voyager 2 had five working instruments, including the plasma instrument that failed on Voyager 1. The instruments have a reading of a 20-fold jump in plasma density which confirmed that Voyager 2 had gone across the heliopause. The change occurred over a distance of only 0.005 a.u. as shown in the Figure below.

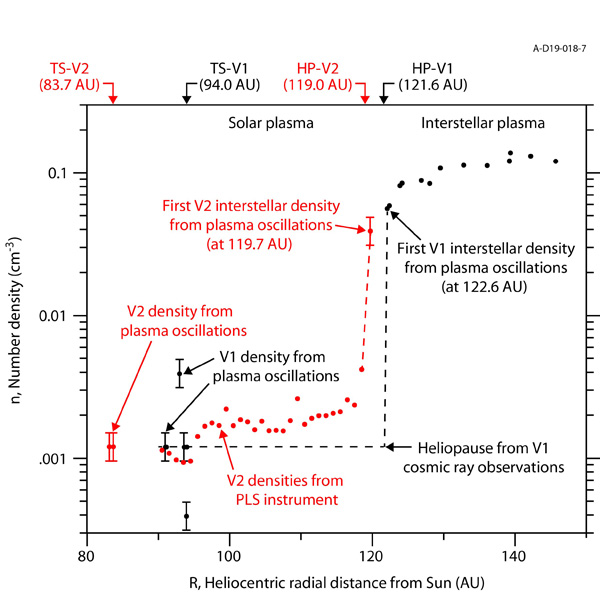
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Figure X. Voyager 1 (V1) black dots and red dots and lines from Voyager 2 (V2) measured in crossing the heliopause in 2019. Particle number densities versus radial distance from the Sun in astronomical units (AU). The plasma densities are inferred from the “from plasma oscillations” are electron densities from the plasma wave instrument (PWS). Densities “from the PLS (plasma) instrument” are proton densities, which are almost the same as the electron densities (Don Gurnett/University of Iowa).

Another marker of the heliopause is a sudden change in the nature of the energetic particles. The energies of solar wind particles is much lower than the those coming from the galaxy at large. As Voyager 2 crossed through the heliopause, it measured the low-energy ions from the solar wind dropping away, replaced by galactic cosmic rays produced in distant and long-ago supernova explosions.

However, Voyager 2 saw no sudden shift in magnetic field accompanying the changes in particle density — in sharp contrast to Voyager 1’s observations in Fig. X showing sharp jump in the plasma density. Leonard Burlaga (NASA Goddard) and coinvestigator on the Voyagers’ plasma and magnetic field experiments conclouded that there is plasma physics transitional process that coordinates the magnetic field across this transitional layer that is not fully understood.

What was also surprising was that both spacecraft had crossed the heliopause at roughly the same distance from the Sun: 121.6 a.u. and 119 a.u. (a.u. -astronomical units) respectively. Voyager 1 made its move as the Sun was nearing a peak in solar activity that sent out regular “explosions” of plasma and energy from coronal mass ejections. By the time Voyager 2 went across, though, the Sun's had quieted. The heliopause was expected to have “breathed in” during this time, yet both spacecraft went over the boundary at approximately the same distance. Burlaga is reported to have said that “If we take our models at face value, we would have expected a difference.”

Density measurements show that both spacecraft crossed the heliopause in under a day, yet neither one saw a whole boundary. Voyager 1 saw the outside leaking in, says Edward Stone (NASA-JPL), Voyager’s project scientist and lead of another study: “Even before we left the heliosphere, we had two episodes where we were connected to the outside.” The interstellar medium had penetrated the heliopause in these instances and invaded the heliosphere.

For Voyager 2, Stone says, the situation was reversed. Even after its heliopause crossing, the spacecraft was still detecting particles originating in the solar wind. This time, the inside was leaking out.

Observations from both craft revealed the full complexity of the heliopause. Voyager 1 saw a “stagnation region” before the heliopause, where particle velocities dropped near zero, but Voyager 2 did not see anything like that. Instead, Voyager 2 saw multiple boundary layers inside the heliopause. Both spacecraft saw a boundary layer extending at least 10 a.u. past the heliopause, a region that Gurnett likened to the [boundary layer that forms when air flows over an airplane wing](https://howthingsfly.si.edu/aerodynamics/friction-drag).

### Ad Astra

Next up, technically speaking, is the bow wave that forms ahead of the heliosphere as it travels through the interstellar medium, like the bow wave that forms at the prow of a ship. Depending on how fast the solar system travels relative to the interstellar plasma around the solar plasma, this bow wave may even be a shock, more akin to the bow shock in front of a fighter jet. Unfortunately, even as the Voyagers continue to zip along at 3 a.u. per year, they won’t reach this boundary with working instruments. Stone estimates the Voyagers only have another five years of power left. And they’ll be the last probes to pass through these boundaries for at least the [next 25 years](https://www.skyandtelescope.com/observing/celestial-objects-to-watch/space-satellites/how-to-see-interstellar-space-probes/).

Instead, Stone reports, that the goal is to measure the true interstellar medium, the plasma that is undisturbed by the Sun’s magnetic field and the particles it sends out. “We will measure as far from the heliosphere as we can.”

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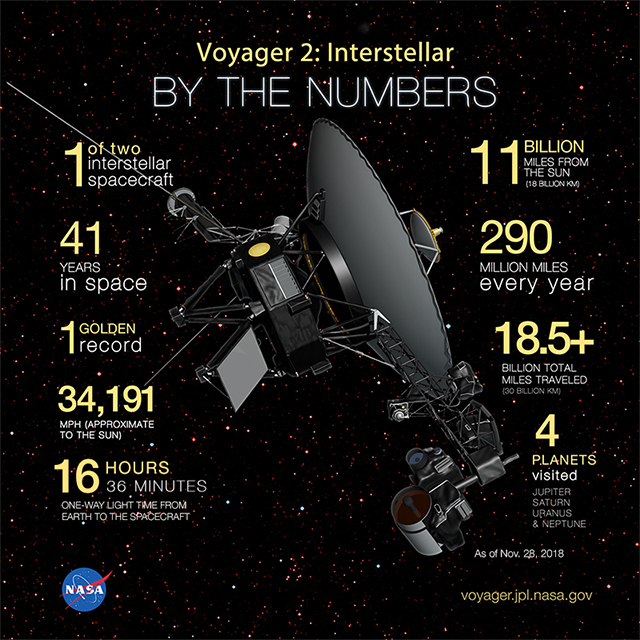
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The **Voyager 1 and 2** Saturn encounters occurred nine months apart, in November **1980** and August 1981. **Voyager 1** is leaving the solar system. **Voyager 2** completed its encounter with Uranus in January 1986 and with Neptune in August 1989, and is now also en route out of the solar system.

For the second time in history, a human-made object has reached the space between the stars. NASA's [Voyager 2](https://www.nasa.gov/mission_pages/voyager/index.html) probe exited the heliosphere in 2019. The heliosphere is the protective plasma bubble of particles and magnetic fields created by the Sun.

Comparing data from different instruments aboard the two V1 and V2 spacecrafts, mission scientists determined the probe crossed the outer edge of the heliosphere on Nov. 5. This boundary, called the heliopause, is where the tenuous, hot solar wind meets the cold, dense interstellar medium. Its twin, [Voyager 1](https://www.nasa.gov/mission_pages/voyager/voyager20130912.html), crossed this boundary in 2012, but Voyager 2 carries a working instrument that will provide first-of-its-kind observations of the nature of this gateway into interstellar space.

Voyager 2 now is slightly more than 11 billion miles (18 billion kilometers) from Earth. Mission operators still can communicate with Voyager 2 as it enters this new phase of its journey, but information - moving at the speed of light - takes about 16.5 hours to travel from the spacecraft to Earth. By comparison, light traveling from the Sun takes about eight minutes to reach Earth.



Artist's concept of Voyager 2 with 9 facts listed around it. j

"Working on Voyager makes me feel like an explorer, because everything we're seeing is new," said John Richardson, principal investigator for the PLS instrument and a principal research scientist at the Massachusetts Institute of Technology in Cambridge. "Even though Voyager 1 crossed the heliopause in 2012, it did so at a different place and a different time, and without the PLS data. So we're still seeing things that no one has seen before."

In addition to the plasma data, Voyager's science team members have seen evidence from three other onboard instruments - the cosmic ray subsystem, the low energy charged particle instrument and the magnetometer - that is consistent with the conclusion that Voyager 2 has crossed the heliopause. Voyager's team members are eager to continue to study the data from these other onboard instruments to get a clearer picture of the environment through which Voyager 2 is traveling.

"There is still a lot to learn about the region of interstellar space immediately beyond the heliopause," said Ed Stone, Voyager project scientist based at Caltech in Pasadena, California.

Together, the two Voyagers provide a detailed glimpse of how our heliosphere interacts with the constant interstellar wind flowing from beyond. Their observations complement data from NASA's Interstellar Boundary Explorer ([IBEX](https://www.nasa.gov/mission_pages/ibex/index.html)), a mission that is remotely sensing that boundary. NASA also is preparing an additional mission - the upcoming Interstellar Mapping and Acceleration Probe ([IMAP](https://www.nasa.gov/press-release/nasa-selects-mission-to-study-solar-wind-boundary-of-outer-solar-system)), due to launch in 2024 - to capitalize on the Voyagers' observations.

"Voyager has a very special place for us in our heliophysics fleet," said Nicola Fox, director of the Heliophysics Division at NASA Headquarters. "Our studies start at the Sun and extend out to everything the solar wind touches. To have the Voyagers sending back information about the edge of the Sun's influence gives us an unprecedented glimpse of truly uncharted territory."

While the probes have left the heliosphere, Voyager 1 and Voyager 2 have not yet left the solar system, and won't be leaving anytime soon. The boundary of the solar system is considered to be beyond the outer edge of the [Oort Cloud](https://solarsystem.nasa.gov/solar-system/oort-cloud/overview/), a collection of small objects that are still under the influence of the Sun's gravity. The width of the Oort Cloud is not known precisely, but it is estimated to begin at about 1,000 astronomical units (AU) from the Sun and to extend to about 100,000 AU. One AU is the distance from the Sun to Earth. It will take about 300 years for Voyager 2 to reach the inner edge of the Oort Cloud and possibly 30,000 years to fly beyond it.

The Voyager probes are powered using heat from the decay of radioactive material, contained in a device called a radioisotope thermal generator ([RTG](https://voyager.jpl.nasa.gov/mission/spacecraft/instruments/rtg/)). The power output of the RTGs diminishes by about four watts per year, which means that various parts of the Voyagers, including the cameras on both spacecraft, have been turned off over time to manage power.

"I think we're all happy and relieved that the Voyager probes have both operated long enough to make it past this milestone," said Suzanne Dodd, Voyager project manager at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California. "This is what we've all been waiting for. Now we're looking forward to what we'll be able to learn from having both probes outside the heliopause."

Voyager 2 launched in 1977, 16 days before Voyager 1, and both have traveled well beyond their original destinations. The spacecraft were built to last five years and conduct close-up studies of Jupiter and Saturn. However, as the mission continued, additional flybys of the two outermost giant planets, Uranus and Neptune, proved possible. As the spacecraft flew across the solar system, remote-control reprogramming was used to endow the Voyagers with greater capabilities than they possessed when they left Earth. Their two-planet mission became a four-planet mission. Their five-year lifespans have stretched to 41 years, making Voyager 2 NASA's longest running mission.

The Voyager story has impacted not only generations of current and future scientists and engineers, but also Earth's culture, including film, art and music. Each spacecraft carries a [Golden Record](https://www.nasa.gov/content/mementos-of-earth) of Earth sounds, pictures and messages. Since the spacecraft could last billions of years, these circular time capsules could one day be the only traces of human civilization.

Voyager's mission controllers communicate with the probes using NASA's Deep Space Network ([DSN](https://www.nasa.gov/directorates/heo/scan/services/networks/dsn)), a global system for communicating with interplanetary spacecraft. The DSN consists of three clusters of antennas inGoldstone, California; Madrid, Spain; and Canberra, Australia.

The Voyager Interstellar Mission is a part of NASA's Heliophysics System Observatory, sponsored by the Heliophysics Division of NASA's Science Mission Directorate in Washington. JPL built and operates the twin Voyager spacecraft. NASA's DSN, managed by JPL, is an international network of antennas that supports interplanetary spacecraft missions and radio and radar astronomy observations for the exploration of the solar system and the universe. The network also supports selected Earth-orbiting missions. The Commonwealth Scientific and Industrial Research Organisation, Australia's national science agency, operates both the Canberra Deep Space Communication Complex, part of the DSN, and the Parkes Observatory, which NASA has been using to downlink data from Voyager 2 since Nov. 8.

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Riccardo Tommasini Livermore

# 61st Annual Meeting of the APS Division of Plasma Physics

## Volume 64, Number 11

## Monday–Friday, October 21–25, 2019; Fort Lauderdale, Florida

### High resolution imaging of inertially confined fusion implosions using Compton radiography Inertial Confinement Fusion experiments aim to impose the highest possible temperatures and pressures on the fusing ions by compressing a spherical ablator and layer of cryogenic deuterium-tritium fuel with the maximum degree of uniformity. Direct and multiple imaging of the ablator and fusing fuel as they go through maximum compression is fundamental to understand the dynamics of the asymmetries and the amount by which they degrade the implosion efficiency. Here we report on the first radiographs of cryogenic indirect drive implosions. We have used pairs of laser-generated, point-projection, backlighters to generate X-rays with energies exceeding 50keV and record two radiographs, spaced in time, of the fuel near stagnation in implosions experiments at the National Ignition Facility. The radiographs, with a spatial and temporal resolution of ~10 m and ~3 ps, respectively, allow measurements of areal mass densities and the reconstruction of the fuel density profiles. We will discuss the direct measurements of fuel non-uniformities resulting from drive asymmetries and hydro-instabilities, peak and areal densities, and kinetic energy, with emphasis on the impact of these parameters on performance.

bright x ray sources to view

laser implosions

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Defending Planet Earth

Didymos B is small target

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