Appendix 1. Notation

Latin alphabet

Symbol	*Description*	*Introduced in Section (Formula)*
a	current layer half-thickness	8.3
$\mathbf{A}$	vector potential of a magnetic field	6.2
b	half-width of a reconnecting current layer (RCL)	8.3
$\mathbf{b}$	perturbation of a magnetic field	20.2.1
$\mathbf{B}$	magnetic field	1.2
$\mathbf{B}_\tau$	tangential magnetic field	16.2
e, e_a	electric charge	1.2
$\mathbf{e}_\text{c}$	unit vector from the curvature centre	5.2
$\mathcal{E}$	energy of a particle	5.1
$\mathbf{E}$	electric field	1.2
$\mathbf{E}_\text{u}$	electric field in the plasma rest-frame	11.1
f_k	averaged distribution function for particles of kind k	1.1
f_{kl}	binary correlation function	2.2
f_{kln}	triple correlation function	2.3
$\hat{f}_k$	exact distribution function for particles of kind k	2.2
F	complex potential	14.2
$\mathbf{F}, \mathbf{F}_k$	force	1.1
$\langle \mathbf{F}_k \rangle_v$	mean force per unit volume	9.1
$\mathbf{F}_{\mathbf{kl}}$	force density in the phase space	2.2
$\mathbf{F}'$	fluctuating force	2.1
g	velocity-integrated correlation function	3.2

G	gravitational constant	1.2
$\mathbf{G}$	energy flux density	(1.52)
$\mathbf{h}$	magnetic field at a wave front	20.1
Ha	Hartmann number	20.2
$\mathbf{j}$	electric current density	1.2
$\mathbf{j}'$	current density in the plasma rest-frame	11.1
$\mathbf{j}_k^{\mathrm{q}}$	current density due to particles of kind k	9.1
$\mathbf{j}_k$	particle flux density in the phase space	3.1
J	electric current	19.3
k	friction coefficient	1.1
$\mathbf{k}$	wave vector	15.1
$\mathcal{K}$	kinetic energy of a particle	(5.58)
m	magnetic dipole moment	14.4
m, m_a	particle mass	1.2
M	mass of star	19.1
$\mathcal{M}$	magnetic moment of a particle	5.2
	magnetic energy of a system	19.1
n, n_k	number density	8.1
$\mathbf{n}$	unit vector along a magnetic field	5.1
N_k	number of particles of kind k	1.1
p_k	gas pressure of particles of kind k	9.1
p_{m}	magnetic pressure	15.1
$p_{\alpha\beta}$	pressure tensor	9.1
$\mathbf{p}$	particle momentum	5.1
$\mathbf{P}$	generalized momentum	6.2
q	generalized coordinate	6.2
$\mathbf{q}$	heat flux density	12.1
$\mathbf{q}_k$	heat flux density due to particles of kind k	9.1
Q_k	rate of energy release in a gas of particles of kind k	9.1
r_{D}	Debye radius	8.2
r_{L}	Larmor radius	5.1
$\mathbf{r}_a$	coordinates of ath particle	1.2
R	radius of star	14.4
$R_{\perp}$	guiding centre spiral radius	5.2
$\mathcal{R}$	rigidity of a particle	5.1
$\mathbf{R}$	guiding centre vector	5.2
Re	Reynolds number	12.3
Re_{m}	magnetic Reynolds number	12.3
s	entropy per unit mass	12.2
T	temperature	12.2
	kinetic energy of a macroscopic motion	19.1
T_{B}	period of the Larmor rotation	5.2
$T_{\alpha\beta}$	Maxwellian stress tensor	12.1

$\mathbf{u}$	relative velocity	5.1
	velocity of the centre-of-mass system	11.1
$\mathbf{u}_e$	mean electron velocity	11.1
$\mathbf{u}_i$	mean ion velocity	11.1
$\mathbf{u}_k$	mean velocity of particles of kind k	9.1
U	interaction potential	8.1
	volume of a fluid particle	14.2
	specific volume of a magnetic tube	19.3
U_{th}	thermal energy	19.1
$\mathbf{U}$	velocity of the moving reference frame	16.2
	shock speed	17.1
$\mathbf{v}$	macroscopic velocity of a plasma	12.2
$\mathbf{v}, \mathbf{v}_a$	particle velocity	1.2
$\mathbf{v}_{\mathrm{d}}$	drift velocity	5.1
v_{n}	normal component of the velocity	16.2
v_x	velocity orthogonal to a discontinuity surface	16.1
$\mathbf{v}\,'$	deviation of particle velocity from its mean value	9.1
$\mathbf{v}_\tau$	tangential velocity	16.1
$v_{\parallel}$	velocity component along the magnetic field lines	5.1
$v_{\perp}$	transversal velocity	5.1
V_{A}	Alfvén speed	13.1
$\mathbf{V}_{\mathrm{gr}}$	group velocity of a wave	15.1
$\mathbf{V}_{\mathrm{ph}}$	phase velocity of a wave	15.1
V_{s}	sound speed velocity	15.1
V_{Te}	mean thermal velocity of electons	(5.54)
V_{Ti}	mean thermal velocity of ions	(5.53)
V_{Tp}	mean thermal velocity of protons	(5.55)
$V_{\pm}$	speed of a fast (slow) magnetoacoustic wave	15.1
w	probability density	2.1
w, w_k	heat function per unit mass	9.1
W	energy density of an electromagnetic field	(1.51)
X	phase space	1.1
Z	ion charge number	8.2

Greek alphabet

Symbol	*Description*	*Introduced in Section (Formula)*
$\alpha_{\rm B}$	parameter of the magnetic field inhomogeneity	5.2
$\alpha_{\rm E}$	parameter of the electric field inhomogeneity	5.2
β	coefficient in an expulsion force	20.3
γ	dimensionless parameter of ideal MHD	13.1
γ_g	ratio of specific heats	16.1
Γ	$6N$-dimensional phase space	2.1
δ	dimensionless parameter of ideal MHD	12.3
ε	mean kinetic energy of a chaotic motion	12.1
	dimensionless parameter of ideal MHD	13.1
ζ	second viscosity coefficient	12.2
$\zeta_{\rm i}$	interaction parameter	3.1
$\zeta_{\rm p}$	plasma parameter	3.1
η	first viscosity coefficient (dynamic viscosity)	12.2
θ	pitch-angle	5.1
	angle between a wave vector and the magnetic field	15.1
$\kappa_{\rm e}$	classical electron conductivity	8.3
λ	mean free path	8.1
$\ln \Lambda$	Coulomb logarithm	8.1
ν	collisional frequency	8.1
ν	kinematic viscosity	12.2
ν_{ei}	electron-ion mean collisional frequency	11.1
ν_{kl}	mean collisional frequency	9.1
$\nu_{\rm m}$	magnetic diffusivity	12.2
ξ	column depth	8.3
$\pi_{\alpha\beta}^{(k)}$	viscous stress tensor	9.1
$\Pi_{\alpha\beta}^{*}$	total momentum flux density tensor	12.2
ρ	plasma mass density	9.1
ρ_k	mass density for particles of kind k	9.1
$\rho^{\rm q}$	electric charge density	1.2
$\rho_k^{\rm q}$	charge density due to particles of kind k	9.1

$\boldsymbol{\rho}$	rotational motion vector	5.2
σ	isotropic electric conductivity	11.1
σ_{H}	Hall conductivity	11.1
$\sigma_{\parallel}$	conductivity parallel to the magnetic field	11.1
$\sigma_{\perp}$	conductivity perpendicular to the magnetic field	11.1
$\sigma_{\alpha\beta}^{\mathrm{v}}$	viscous stress tensor	12.2
τ	characteristic time scale	5.2
τ_{ee}	electron collisional time	8.3
τ_{ei}	electron-ion collisional time	8.3
τ_{ii}	ion collisional time	8.3
ϕ	gravitational potential	1.2
φ	electrostatic potential	8.2
φ	angle in the spherical frame	14.4
ϕ, φ	angle in the cylindrical frame	19.2
$\hat{\varphi}_k$	deviation of the exact distribution function	
	from an averaged distribution function	2.2
Φ	magnetic flux	14.2
	stream function	14.4
χ	deflection angle	8.1
ψ	angle to the x axis	14.4
	potential of an electric current	20.3
Ψ	potential of a current-free magnetic field	13.1
ω	wave frequency	15.1
ω_0	wave frequency in a moving frame of reference	15.1
ω_{B}	cyclotron or Larmor frequency	5.1
ω_{pl}	electron plasma frequency	8.2
Ω	gravitational energy	19.1
$\boldsymbol{\omega}$	vector of angular velocity	20.1

Appendix 2
Useful Expressions

Source formulae

Larmor frequency of a non-relativistic electron (5.11), (5.51)

$$\omega_{\mathrm{B}}^{(\mathrm{e})} = \frac{eB}{m_{\mathrm{e}}c} \approx 1.76 \times 10^7\, B\,(\mathrm{G})\,, \;\; \mathrm{rad\ s^{-1}}\,.$$

Larmor frequency of a non-relativistic proton (5.52)

$$\omega_{\mathrm{B}}^{(\mathrm{p})} \approx 9.58 \times 10^3\; B\,(\mathrm{G})\,, \;\; \mathrm{rad\ s^{-1}}\,.$$

Larmor radius of a non-relativistic electron (5.14), (5.59)

$$r_{\mathrm{L}}^{(\mathrm{e})} = \frac{c\,p_{\perp}}{eB} \approx 5.69 \times 10^{-8}\; \frac{v\,(\mathrm{cm\,s^{-1}})}{B\,(\mathrm{G})}\,, \;\; \mathrm{cm}\,.$$

Larmor radius of a non-relativistic proton (5.14), (5.61)

$$r_{\mathrm{L}}^{(\mathrm{p})} \approx 1.04 \times 10^{-4}\; \frac{v\,(\mathrm{cm\,s^{-1}})}{B\,(\mathrm{G})}\,, \;\; \mathrm{cm}\,.$$

Mean thermal velocity of electrons (5.54)

$$V_{\mathrm{Te}} = \left(\frac{3k_{\mathrm{B}}\, T_{\mathrm{e}}}{m_{\mathrm{e}}} \right)^{1/2} \approx 6.74 \times 10^5 \sqrt{T_{\mathrm{e}}\,(\mathrm{K})}\,, \;\; \mathrm{cm\ s^{-1}}\,.$$

Mean thermal velocity of protons (5.55)

$$V_{\mathrm{Tp}} \approx 1.57 \times 10^4 \sqrt{T_{\mathrm{p}}\,(\mathrm{K})}\,, \;\; \mathrm{cm\ s^{-1}}\,.$$

Larmor radius of non-relativistic *thermal* electrons (5.56)

$$r_{\mathrm{L}}^{(\mathrm{e})} = \frac{V_{\mathrm{Te}}}{\omega_{\mathrm{B}}^{(\mathrm{e})}} \approx 3.83 \times 10^{-2}\; \frac{\sqrt{T_{\mathrm{e}}\,(\mathrm{K})}}{B\,(\mathrm{G})}\,, \;\; \mathrm{cm}\,.$$

Larmor radius of non-relativistic *thermal* protons (5.57)

$$r_{\rm L}^{(\rm p)} = \frac{V_{\rm Tp}}{\omega_{\rm B}^{(\rm p)}} \approx 1.64\ \frac{\sqrt{T_{\rm p}\,({\rm K})}}{B\,({\rm G})}\,,\ \ {\rm cm}\,.$$

Drift velocity (5.20)

$$\mathbf{v}_{\rm d} = \frac{c}{e}\ \frac{\mathbf{F}\times\mathbf{B}}{B^{2}}\,.$$

Magnetic moment of a particle on the Larmor orbit (6.6)

$$\mathcal{M} = \frac{1}{c}\,JS = \frac{e\,\omega_{\rm B}\,r_{\rm L}^{2}}{2c} = \frac{p_{\perp}^{2}}{2mB} = \frac{\mathcal{E}_{\perp}}{B}\,.$$

Debye radius ($T_{\rm e} = T\,,\ T_{\rm i} = 0$ or $T_{\rm e} \gg T_{\rm i}$) (8.33)

$$r_{\rm D} = \left(\frac{k_{\rm B} T}{4\pi\, n e^{2}}\right)^{1/2}.$$

Debye radius in electron-proton thermal plasma ($T_{\rm e} = T_{\rm p} = T$) (8.77)

$$r_{\rm D} = \left(\frac{k_{\rm B} T}{8\pi\, e^{2}\, n}\right)^{1/2} \approx 4.9\,\left(\frac{T}{n}\right)^{1/2}\,,\ \ {\rm cm}\,.$$

Coulomb logarithm (8.75)

$$\ln\Lambda = \ln\left[\left(\frac{3k_{\rm B}^{3/2}}{2\pi^{1/2}\,e^{3}}\right)\left(\frac{T_{\rm e}^{3}}{n_{\rm e}}\right)^{1/2}\right] \approx \ln\left[1.25\times10^{4}\,\left(\frac{T_{\rm e}^{3}}{n_{\rm e}}\right)^{1/2}\right].$$

Electron plasma frequency (8.78)

$$\omega_{pl}^{(\rm e)} = \left(\frac{4\pi\, e^{2}\, n_{\rm e}}{m_{\rm e}}\right)^{1/2} \approx 5.64\times10^{4}\,\sqrt{n_{\rm e}}\,,\ \ {\rm rad\ s^{-1}}\,.$$

Thermal electron collisional time (8.80)

$$\tau_{\rm ee} = \frac{m_{\rm e}^{2}}{0.714\ e^{4}\,8\pi\,\ln\Lambda}\ \frac{V_{\rm Te}^{3}}{n_{\rm e}} \approx 4.04\times10^{-20}\ \frac{V_{\rm Te}^{3}}{n_{\rm e}}\,,\ \ {\rm s}\,.$$

Thermal proton collisional time (8.81)

$$\tau_{\rm pp} = \frac{m_{\rm p}^{2}}{0.714\ e^{4}\,8\pi\,\ln\Lambda}\ \frac{V_{\rm Tp}^{3}}{n_{\rm p}} \approx 1.36\times10^{-13}\ \frac{V_{\rm Tp}^{3}}{n_{\rm p}}\,,\ \ {\rm s}\,.$$

Electron-ion collision (energy exchange) time Section 8.3

$$\tau_{\rm ei}\,(\mathcal{E}) = \frac{m_{\rm e} m_{\rm i}\,[\,3k_{\rm B}\,(T_{\rm e}/m_{\rm e} + T_{\rm i}/m_{\rm i})\,]^{3/2}}{e_{\rm e}^{2}\,e_{\rm i}^{2}\,(6\pi)^{1/2}\,8\,\ln\Lambda}\,.$$

Time of energy exchange between electrons and protons (8.44)

$$\tau_{\rm ep}\,(\mathcal{E}) \approx 22\,\tau_{\rm pp} \approx 950\,\tau_{\rm ee}\,.$$

Dreicer field (8.83)

$$E_{\rm Dr} = \frac{4\pi e^3 \ln\Lambda}{k_{\rm B}}\,\frac{n_{\rm e}}{T_{\rm e}} \approx 6.54\times 10^{-8}\,\frac{n_{\rm e}}{T_{\rm e}}\,,\ \ {\rm V\,cm^{-1}}\,.$$

Conductivity of magnetized plasma Section 11.3

$$\sigma_{\parallel} = \sigma = \frac{e^2 n}{m_{\rm e}}\,\tau_{\rm ei} \approx 2.53\times 10^8\, n\,({\rm cm^{-3}})\,\tau_{\rm ei}\,({\rm s})\,,\ \ {\rm s^{-1}}\,,$$

$$\sigma_{\perp} = \sigma\,\frac{1}{1+\left(\omega_{\rm B}^{(\rm e)}\,\tau_{\rm ei}\right)^2}\,, \qquad \sigma_{\rm H} = \sigma\,\frac{\omega_{\rm B}^{(\rm e)}\,\tau_{\rm ei}}{1+\left(\omega_{\rm B}^{(\rm e)}\,\tau_{\rm ei}\right)^2}\,.$$

Magnetic diffusivity (or viscosity) (12.49)

$$\nu_{\rm m} = \frac{c^2}{4\pi\sigma} \approx 7.2\times 10^{19}\,\frac{1}{\sigma}\,,\ \ {\rm cm^2\,s^{-1}}\,.$$

Magnetic Reynolds number (12.62)

$${\rm Re_m} = \frac{L^2}{\nu_{\rm m}\,\tau} = \frac{vL}{\nu_{\rm m}}$$

Alfvén speed (13.14), (13.34)

$$V_{\rm A} = \frac{B}{\sqrt{4\pi\rho}} \approx 2.18\times 10^{11}\,\frac{B}{\sqrt{n}}\,,\ \ {\rm cm\ s^{-1}}\,.$$

Sound speed in electron-proton plasma (16.98)

$$V_s = \left(\gamma_g\,\frac{p}{\rho}\right)^{1/2} \approx 1.66\times 10^4\,\sqrt{T({\rm K})}\,,\ \ {\rm cm\ s^{-1}}\,.$$

Electric field in magnetized plasma (19.71)

$$E \approx \frac{1}{c}\,vB \approx 10^{-8}\ v\,({\rm cm\ s^{-1}})\,B\,({\rm G})\,,\ \ {\rm V\ cm^{-1}}\,.$$

Appendix 3. Constants

Fundamental physical constants

Speed of light	c	2.998×10^{10} cm s^{-1}
Electron charge	e	4.802×10^{-10} CGSE
Electron mass	m_e	9.109×10^{-28} g
Proton mass	m_p	1.673×10^{-24} g
Boltzmann constant	k_{B}	1.381×10^{-16} erg K^{-1}
Gravitational constant	G	6.673×10^{-8} dyne cm^2 g^{-2}
Planck's constant	h	6.625×10^{-27} erg s

Some useful constants and units

Ampere (current)	A	3×10^9 CGSE
Angström (length)	A	10^{-8} cm
Electron Volt (energy)	eV	1.602×10^{-12} erg
	eV	11605 K
Gauss (magnetic induction)	G	3×10^{10} CGSE
Henry (inductance)	H	1.111×10^{-12} s^2 cm^{-1}
Ionization potential of hydrogen		13.60 eV
Joule (energy)	J	10^7 erg
Maxwell (magnetic flux)	M	3×10^{10} CGSE
Ohm (resistance)	Ω	1.111×10^{-12} s cm^{-1}
Tesla (magnetic induction)		10^4 Gauss
Volt (potential)	V	3.333×10^{-3} CGSE
Watt (power)	W	10^7 erg s^{-1}
Weber (magnetic flux)	Wb	10^8 Maxwell

Some astrophysical constants

Astronomical unit	AU	1.496×10^{13} cm
Mass of the Sun	$M_\odot$	1.989×10^{33} g

Mass of the Earth	M_E	5.98×10^{27} g
Solar radius	$R_\odot$	6.960×10^{10} cm
Solar surface gravity	$g_\odot$	2.740×10^{4} cm s^{-2}
Solar luminosity	$L_\odot$	3.827×10^{33} erg s^{-1}
Mass loss rate	$\dot{M}_\odot$	10^{12} g s^{-1}
Rotation period of the Sun	$T_\odot$	26 days (at equator)

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Appendix 1. Acronyms

Acronym	*Meaning*
ACE	Advanced Composition Explorer
CME	coronal mass ejection
CDS	Coronal Diagnostic Spectrometer
EIT	Extreme ultraviolet Imaging Telescope
FFF	force free (magnetic) field
FIP	first ionization potential
GOES	Geostationary Operational Environmental Satellite
GONG	Global Oscillation Network Group
LDE	long duration event
MDI	Michelson Doppler Imager
PNL	polarity inversion line (of the photospheric magnetic field)
RCL	reconnecting current layer
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
SHTCL	super-hot turbulent-current layer
SNL	simplified neutral line (of the photospheric magnetic field)
SOHO	Solar and Heliospheric Observatory
SEPs	solar energetic particles
TRACE	Transition Region and Coronal Explorer
VLA	Very Large Array

Appendix 2. Notation

Latin alphabet

Symbol	*Description*	*Introduced in Section (Formula)*
$\mathbf{A}$	vector potential of a magnetic field	1.1
d	thickness of non-adiabatic region	9.1
h	magnetic field gradient	1.1
H	Hamiltonian	9.2
$\mathcal{H}$	magnetic helicity	12.1
K	curvature of a magnetic field line	9.2
l	current layer length	13
$L\,(T)$	radiative loss function	13
$\mathbf{u}$	electric current velocity	2.3
V	velocity of the plasma flow	13
$V_{\rm a}$	gradient of the Alfvén speed	2.1
x	ionisation degree	13

Greek alphabet

Symbol	*Description*	*Introduced in Section (Formula)*
ε	dimensionless electric field	9.1
ε_α	small parameter of expansion	10.3
ν_{ni}	neutral-ion mean collisional frequency	13
ξ	displacement of a current layer	10.3
$\xi_\parallel$	dimensionless longitudinal magnetic field	9.1
$\xi_\perp$	dimensionless transverse magnetic field	9.1
$\boldsymbol{\xi}$	displacement of the medium	2.1
Π	work against the Lorentz force	11.4
τ_r	reconnection time scale	14.4

Appendix 3
Useful Formulae

The most important characteristics of astrophysical plasmas (for more detail see vol. 1, Plasma Astrophysics: Fundamental and Practice)

Alfvén speed

$$V_{\mathrm{A}} = \frac{B}{\sqrt{4\pi\rho}} \approx 2.18 \times 10^{11} \, \frac{B}{\sqrt{n}} \,, \quad \mathrm{cm\ s^{-1}} \,.$$

Conductivity of magnetized plasma

$$\sigma_{\parallel} = \sigma = \frac{e^2 n}{m_{\mathrm{e}}} \, \tau_{\mathrm{ei}} \approx 2.53 \times 10^8 \, n \, (\mathrm{cm^{-3}}) \, \tau_{\mathrm{ei}} \, (\mathrm{s}) \,, \quad \mathrm{s^{-1}} \,,$$

$$\sigma_{\perp} = \sigma \, \frac{1}{1 + \left(\omega_{\mathrm{B}}^{(\mathrm{e})} \, \tau_{\mathrm{ei}} \right)^2} \,, \qquad \sigma_{\mathrm{H}} = \sigma \, \frac{\omega_{\mathrm{B}}^{(\mathrm{e})} \, \tau_{\mathrm{ei}}}{1 + \left(\omega_{\mathrm{B}}^{(\mathrm{e})} \, \tau_{\mathrm{ei}} \right)^2} \,.$$

Coulomb logarithm

$$\ln \Lambda = \ln \left[\left(\frac{3 k_{\mathrm{B}}^{3/2}}{2\pi^{1/2} \, e^3} \right) \left(\frac{T_{\mathrm{e}}^3}{n_{\mathrm{e}}} \right)^{1/2} \right] \approx \ln \left[1.25 \times 10^4 \, \left(\frac{T_{\mathrm{e}}^3}{n_{\mathrm{e}}} \right)^{1/2} \right] \,.$$

Cyclotron frequency (or gyrofrequency)

$$\omega_{\mathrm{B}} = \frac{ecB}{\mathcal{E}} \,.$$

Debye radius ($T_{\mathrm{e}} = T \,,\ T_{\mathrm{i}} = 0$ or $T_{\mathrm{e}} \gg T_{\mathrm{i}}$)

$$r_{\mathrm{D}} = \left(\frac{k_{\mathrm{B}} T}{4\pi \, n e^2} \right)^{1/2} \,.$$

Debye radius in electron-proton thermal plasma ($T_e = T_p = T$)

$$r_{\rm D} = \left(\frac{k_{\rm B} T}{8\pi\, e^2\, n} \right)^{1/2} \approx 4.9 \, \left(\frac{T}{n} \right)^{1/2} \, , \ \ {\rm cm}\, .$$

Dreicer electric field

$$E_{\rm Dr} = \frac{4\pi e^3 \ln \Lambda}{k_{\rm B}} \, \frac{n_{\rm e}}{T_{\rm e}} \approx 6.54 \times 10^{-8} \, \frac{n_{\rm e}}{T_{\rm e}} \, , \ \ {\rm V\, cm}^{-1}\, .$$

Drift velocity

$$\mathbf{v}_{\rm d} = \frac{c}{e} \, \frac{\mathbf{F} \times \mathbf{B}}{B^2}\, .$$

Electric drift velocity

$$\mathbf{v}_{\rm d} = c \, \frac{\mathbf{E} \times \mathbf{B}}{B^2}\, .$$

Electric field in magnetized plasma

$$E \approx \frac{1}{c}\, vB \approx 10^{-8} \ v\, ({\rm cm\ s}^{-1})\, B\, ({\rm G})\, , \ \ {\rm V\ cm}^{-1}\, .$$

Electron plasma frequency

$$\omega_{pl}^{(\rm e)} = \left(\frac{4\pi\, e^2\, n_{\rm e}}{m_{\rm e}} \right)^{1/2} \approx 5.64 \times 10^4 \, \sqrt{n_{\rm e}} \, , \ \ {\rm rad\ s}^{-1}\, .$$

Electron-ion collision (energy exchange) time

$$\tau_{\rm ei}\, (\mathcal{E}) = \frac{m_{\rm e} m_{\rm i} \, [\, 3k_{\rm B}\, (T_{\rm e}/m_{\rm e} + T_{\rm i}/m_{\rm i})\,]^{3/2}}{e_{\rm e}^2\, e_{\rm i}^2\, (6\pi)^{1/2}\, 8\, \ln \Lambda}\, .$$

Gradient drift velocity

$$\mathbf{v}_{\rm d} = \frac{\mathcal{M} c}{eB}\, \mathbf{n} \times \nabla B\, .$$

Larmor frequency of a non-relativistic electron

$$\omega_{\rm B}^{(\rm e)} = \frac{eB}{m_{\rm e} c} \approx 1.76 \times 10^7\, B\, ({\rm G})\, , \ \ {\rm rad\ s}^{-1}\, .$$

Larmor frequency of a non-relativistic proton

$$\omega_{\rm B}^{(\rm p)} \approx 9.58 \times 10^3 \ B\, ({\rm G})\, , \ \ {\rm rad\ s}^{-1}\, .$$

Larmor radius of a non-relativistic electron

$$r_{\rm L}^{(\rm e)} = \frac{c\, p_\perp}{eB} \approx 5.69 \times 10^{-8} \, \frac{v\, ({\rm cm\, s}^{-1})}{B\, ({\rm G})}\, , \ \ {\rm cm}\, .$$

Larmor radius of a non-relativistic proton

$$r_{\rm L}^{(\rm p)} \approx 1.04 \times 10^{-4} \; \frac{v\,({\rm cm\,s^{-1}})}{B\,({\rm G})}\,, \;\; {\rm cm}\,.$$

Larmor radius of a non-relativistic *thermal* electrons

$$r_{\rm L}^{(\rm e)} = \frac{V_{\rm Te}}{\omega_{\rm B}^{(\rm e)}} \approx 3.83 \times 10^{-2} \; \frac{\sqrt{T_{\rm e}\,({\rm K})}}{B\,({\rm G})}\,, \;\; {\rm cm}\,.$$

Larmor radius of a non-relativistic *thermal* protons

$$r_{\rm L}^{(\rm p)} = \frac{V_{\rm Tp}}{\omega_{\rm B}^{(\rm p)}} \approx 1.64 \; \frac{\sqrt{T_{\rm p}\,({\rm K})}}{B\,({\rm G})}\,, \;\; {\rm cm}\,.$$

Lundquist number

$$N_{\rm L} = {\rm Re_m}(V_{\rm A}, L) = \frac{V_{\rm A}\,L}{\nu_{\rm m}}\,.$$

Magnetic diffusivity (or viscosity)

$$\nu_{\rm m} = \frac{c^2}{4\pi\sigma} \approx 7.2 \times 10^{19} \; \frac{1}{\sigma}\,, \;\; {\rm cm^2\,s^{-1}}\,.$$

Magnetic moment of a particle on the Larmor orbit

$$\mathcal{M} = \frac{1}{c}\,JS = \frac{e\,\omega_{\rm B}\,r_{\rm L}^2}{2c} = \frac{p_\perp^2}{2mB} = \frac{\mathcal{E}_\perp}{B}\,.$$

Magnetic Reynolds number

$${\rm Re_m} = \frac{L^2}{\nu_{\rm m}\,\tau} = \frac{vL}{\nu_{\rm m}}$$

Mean thermal velocity of electrons

$$V_{\rm Te} = \left(\frac{3k_{\rm B}\,T_{\rm e}}{m_{\rm e}} \right)^{1/2} \approx 6.74 \times 10^5 \sqrt{T_{\rm e}\,({\rm K})}\,, \;\; {\rm cm\ s^{-1}}\,.$$

Mean thermal velocity of protons

$$V_{\rm Tp} \approx 1.57 \times 10^4 \sqrt{T_{\rm p}\,({\rm K})}\,, \;\; {\rm cm\ s^{-1}}\,.$$

Sound speed in electron-proton plasma

$$V_s = \left(\gamma_g\,\frac{p}{\rho} \right)^{1/2} \approx 1.66 \times 10^4 \sqrt{T({\rm K})}\,, \;\; {\rm cm\ s^{-1}}\,.$$

Thermal electron collisional time

$$\tau_{\mathrm{ee}} = \frac{m_{\mathrm{e}}^2}{0.714\ e^4\, 8\pi\ \ln\Lambda}\, \frac{V_{\mathrm{Te}}^3}{n_{\mathrm{e}}} \approx 4.04 \times 10^{-20}\ \frac{V_{\mathrm{Te}}^3}{n_{\mathrm{e}}}\ ,\ \ \mathrm{s}\,.$$

Thermal proton collisional time

$$\tau_{\mathrm{pp}} = \frac{m_{\mathrm{p}}^2}{0.714\ e^4\, 8\pi\ \ln\Lambda}\, \frac{V_{\mathrm{Tp}}^3}{n_{\mathrm{p}}} \approx 1.36 \times 10^{-13}\ \frac{V_{\mathrm{Tp}}^3}{n_{\mathrm{p}}}\ ,\ \ \mathrm{s}\,.$$

Time of energy exchange between electrons and protons

$$\tau_{\mathrm{ep}}\,(\mathcal{E}) \approx 22\,\tau_{\mathrm{pp}} \approx 950\,\tau_{\mathrm{ee}}\,.$$

Appendix 4. Constants

Fundamental physical constants

Speed of light	c	2.998×10^{10} cm s^{-1}
Electron charge	e	4.802×10^{-10} CGSE
Electron mass	m_e	9.109×10^{-28} g
Proton mass	m_p	1.673×10^{-24} g
Boltzmann constant	k_{B}	1.381×10^{-16} erg K^{-1}
Gravitational constant	G	6.673×10^{-8} dyne cm^2 g^{-2}
Planck's constant	h	6.625×10^{-27} erg s

Some useful constants and units

Ampere (current)	A	3×10^9 CGSE
Angström (length)	A	10^{-8} cm
Electron Volt (energy)	eV	1.602×10^{-12} erg
	eV	11605 K
Gauss (magnetic induction)	G	3×10^{10} CGSE
Henry (inductance)	H	1.111×10^{-12} s^2 cm^{-1}
Ionization potential of hydrogen		13.60 eV
Joule (energy)	J	10^7 erg
Maxwell (magnetic flux)	M	3×10^{10} CGSE
Ohm (resistance)	Ω	1.111×10^{-12} s cm^{-1}
Tesla (magnetic induction)		10^4 Gauss
Volt (potential)	V	3.333×10^{-3} CGSE
Watt (power)	W	10^7 erg s^{-1}
Weber (magnetic flux)	Wb	10^8 Maxwell

Some astrophysical constants

Astronomical unit	AU	1.496×10^{13} cm
Mass of the Sun	$M_\odot$	1.989×10^{33} g
Mass of the Earth	M_E	5.98×10^{27} g
Solar radius	$R_\odot$	6.960×10^{10} cm
Solar surface gravity	$g_\odot$	2.740×10^{4} cm s^{-2}
Solar luminosity	$L_\odot$	3.827×10^{33} erg s^{-1}
Mass loss rate	$\dot{M}_\odot$	10^{12} g s^{-1}
Rotation period of the Sun	$T_\odot$	26 days (at equator)

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Color Plates

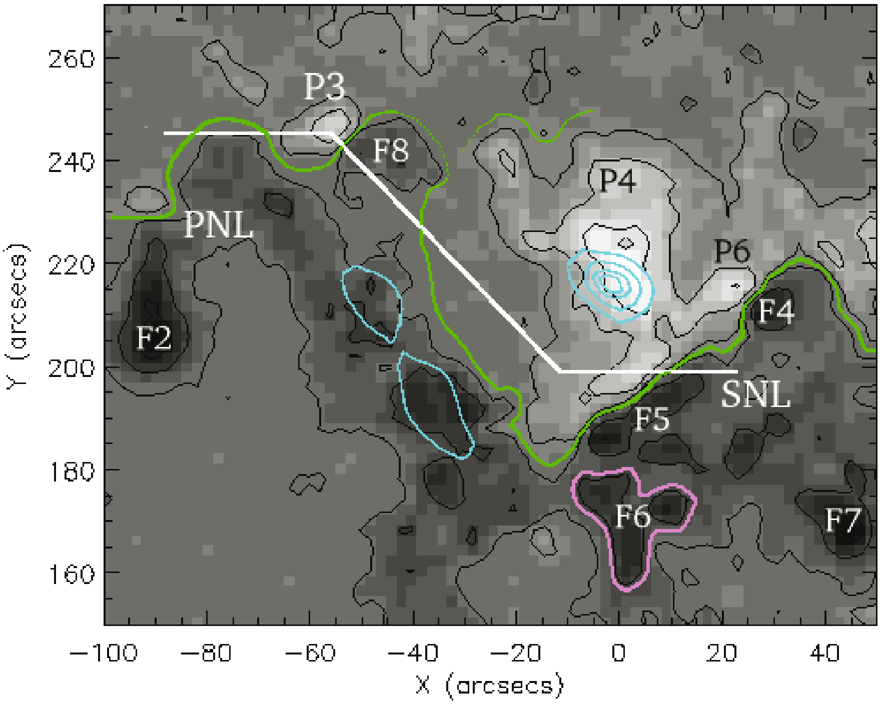

Fig. 4.2. The HXR source contours (blue curves) at the HXR maximum of the Bastille day flare overlaid on the MDI magnetogram. The green curve PNL represents the photospheric neutral line. SNL is the simplified neutral line.

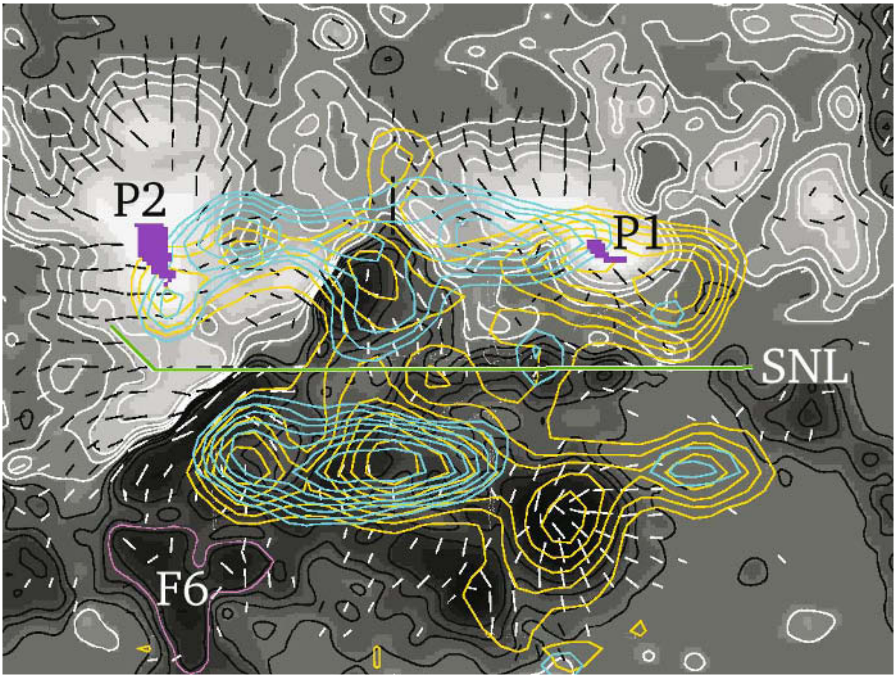

Fig. 4.3. The HXR source positions in the beginning of the first HXR spike S1 (yellow contours) and near its end (blue contours).

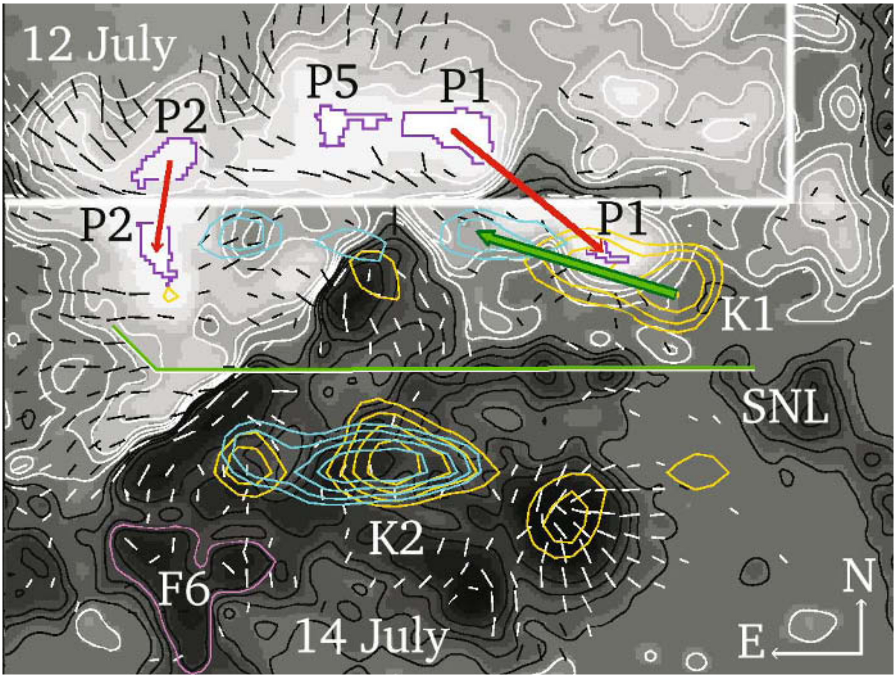

Fig. 4.4. The position and motion of the strongest HXR sources K1 and K2 relative to the SMFT magnetogram on 14 July.

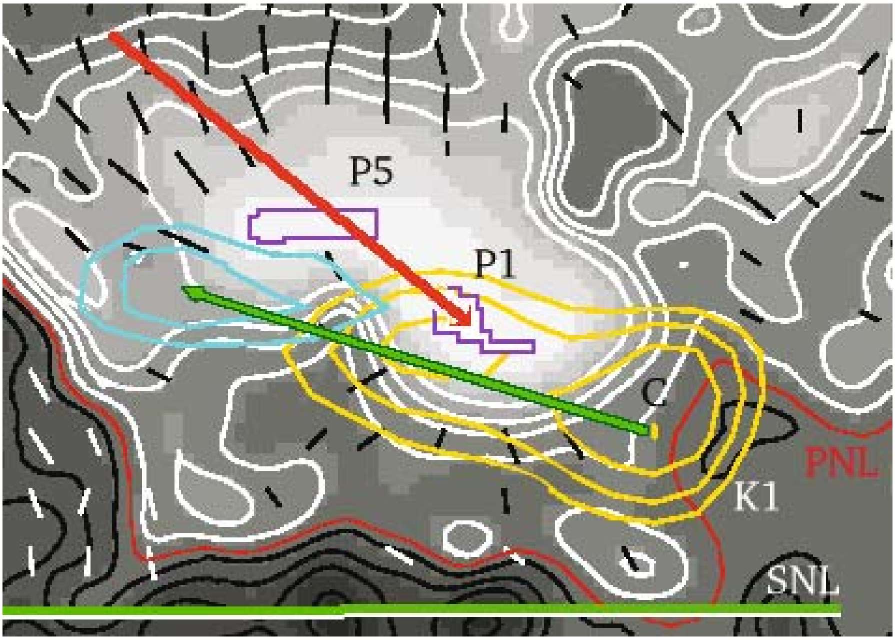

Fig. 4.5. H-band images of the brightest kernel K1 in the rise and decay of the first HXR spike S1 overlaid on the SMFT magnetogram on July 14.