EXTRA MATERIAL
for
MAGNETOHYDRODYNAMICS
of
the SUN
on
PROBLEMS for each CHAPTER
plus
SOLAR OBSERVATORIES and SATELLITES
by

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Problems for the book *Magnetohydrodynamics of the Sun*

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(ii) If the distance to the Sun varies during the Earth's orbit between 1.471×10^{11} m at perihelion and 1.521×10^{11} m at aphelion, show that the distance on the Sun subtended by an angle of 1 arcsec from the Earth varies by ±12 km.

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Suppose that the intensity (I) of part of the photosphere at temperature (T) obeys the *Stefan-Boltzmann law* for black-body radiation, namely, $I = \sigma_{SB}T^4$, where σ_{SB} is constant. Then, if the

temperatures of a sunspot umbra and the ambient photosphere are 3700 K and 5800 K, respectively, by what factor is the umbra less bright than the photosphere?

1.2 Chapter 2

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PROBLEM 2.6. **Diffusion.**
Show that, when there is no $E_{\|}$ and $\mathbf{w}$ exists, in resistive MHD the slippage velocity is simply

$$\mathbf{w} - \mathbf{v} = \frac{\mathbf{j} \times \mathbf{B}}{\sigma\ B^2}.$$

PROBLEM 2.7. **Field Lines.**
For the magnetic field $\mathbf{B} = -y\ \hat{\mathbf{x}} + \hat{\mathbf{y}}$, sketch the magnetic field lines. From the sketch, what do you expect qualitatively the magnetic pressure force and magnetic tension force to be (a) at a point on the x-axis and (b) at a location where $y > 0$. Verify your intuition by calculating the magnetic pressure force, magnetic tension force and Lorentz force explicitly.

PROBLEM 2.8. **Flux Surfaces in Axisymmetric Cylindrical Polars.**
In axisymmetric cylindrical polars (R, ϕ, z), show that the magnetic field can be written

$$(B_R, B_z) = \left(\frac{1}{R}\frac{\partial F}{\partial z}, -\frac{1}{R}\frac{\partial F}{\partial R}\right)$$

in terms of a flux function $[F(R, z)]$.

1.3 Chapter 3

PROBLEM 3.1. **Vector Potential.**
In general, Faraday's law implies that $\mathbf{E} = -\partial\mathbf{A}/\partial t - \boldsymbol{\nabla}\Phi$, where Φ is arbitrary. Show that $\mathbf{A}$ may be redefined to include Φ. In the case of infinite magnetic Reynolds number, deduce the equation that determines $\mathbf{A}$ when $\mathbf{v}$ is given, and also the change $\delta\mathbf{A}$ in $\mathbf{A}$ produced by a displacement $\boldsymbol{\xi}$.

PROBLEM 3.2. **Setting up Euler Potentials.**
If two coordinates (f, g) label field lines, show that in general they may be redefined to make $\mathbf{B} = \boldsymbol{\nabla} f \times \boldsymbol{\nabla} g$.

PROBLEM 3.3. **Vector Potential and Euler Potentials.**
How can the vector potential $\mathbf{A}$ be written in terms of Euler potentials?
(i) Choose the gauge to make $\mathbf{B} \cdot \mathbf{A} = 0$. (
ii) Choose the gauge instead to make a change $\delta\mathbf{A}$ produced by a displacement $\boldsymbol{\xi}$ normal to $\mathbf{B}$, and comment on the consequences.

PROBLEM 3.4. **Nonlinear**
Force-Free Fields. Show that $\boldsymbol{\nabla} \times \mathbf{B} = \alpha\mathbf{B}$ implies that $(\nabla^2 + \alpha^2)\mathbf{B} = \mathbf{B} \times \boldsymbol{\nabla}\alpha$, but that the converse is not true.

PROBLEM 3.5. **Force-Free Fields in Euler Potentials.**
What are the equations for a linear force-free field in Euler potentials? Comment on the result.

PROBLEM 3.6. **Magnetostatic Fields.**
Prove that for a magnetostatic field (i) $\boldsymbol{\nabla} \cdot (\mathbf{B} \times \boldsymbol{\nabla} p) = 0$ and (ii) $(\mathbf{j} \cdot \boldsymbol{\nabla})\mathbf{B} = (\mathbf{B} \cdot \boldsymbol{\nabla})\mathbf{j}$.

PROBLEM 3.7. **General Solution for Magnetostatic Fields.**
Prove that the magnetostatic equations are satisfied by $\mathbf{j} = (\alpha/\mu)\mathbf{B} + \mathbf{B} \times (\boldsymbol{\nabla} p)/B^2$, where α is given by an integral along a field line of the form $\alpha = \alpha_0 - 2\mu \int_{\mathbf{x}_0}^{\mathbf{x}} \mathbf{B} \cdot (\boldsymbol{\nabla} B) \times (\boldsymbol{\nabla} p)/B^4 ds$ from a value α_0 at a reference point $\mathbf{x}_0$, say.

1.4 Chapter 4

PROBLEM 4.1. **Sound Waves in a Flowing Medium.**
Show that sound waves in the presence of a uniform flow $\mathbf{v}_0$ obey a wave equation of the form

$$\left(\frac{\partial}{\partial t} + \mathbf{v}_0 \cdot \boldsymbol{\nabla}\right)^2 \mathbf{v}_1 = c_s^2 \boldsymbol{\nabla}(\boldsymbol{\nabla} \cdot \mathbf{v}_1),$$

and deduce their dispersion relation.

PROBLEM 4.2. **Finite-Amplitude Alfvén Waves.**
Show that a circularly polarised Alfvén wave of arbitrary amplitude propagating along a uniform background magnetic field $(B_0\hat{\mathbf{z}})$ with $\boldsymbol{\nabla} \cdot \mathbf{v} = 0$, $p + B^2/(2\mu) = \textit{constant}$, $\mathbf{v} = \pm\mathbf{b}/\sqrt{(\mu\rho)}$ and $\mathbf{b} = B_0\mathbf{f}(x, y, z \pm V_A t)$ satisfies the ideal MHD equations, where $\mathbf{f}$ is an arbitrary vector with $\boldsymbol{\nabla} \cdot \mathbf{f} = 0$.

PROBLEM 4.3. **Energy Flux in Alfvén Waves.**
Find the magnetic and kinetic energy densities and the Poynting flux in a finite-amplitude, circularly polarised Alfvén wave propagating in the positive z-direction.

PROBLEM 4.4. **Diffusion of Linear Alfvén Waves.**
By adding a term of the form $\eta\nabla^2\mathbf{B}_1$ to the right-hand side of Eq.(4.11), determine the effect of magnetic diffusion on shear Alfvén waves in a uniform medium. If the magnetic Reynolds number is defined as $R_m = v_A/(k\eta)$, find the real and imaginary parts of ω and deduce that, when $R_m \gg 1$, the effect of diffusion is to produce a slow decay of the wave and a small reduction in its frequency of oscillation.

PROBLEM 4.5. **Nonlinear Alfvén Waves with Diffusion.**
Consider a finite-amplitude wave obeying the visco-resistive MHD equations and having a constant total pressure and density and a magnetic field $\mathbf{B}_0 + \mathbf{b}$, where $\mathbf{B}_0 = B_0\hat{\mathbf{z}}$ is uniform. Show that, if $\mathbf{v} = -\mathbf{b}/\sqrt{(\mu\rho)}$ and $\eta = \nu$, then $\mathbf{b}$ satisfies a linear equation and solve it when $\mathbf{b} = b(z,t)\hat{\mathbf{x}}$.

PROBLEM 4.6. **Internal Gravity Waves**.
Use Eq.(4.15) to establish the dispersion relation $\omega = N\ \sin\ \theta_g$ for internal gravity waves when $g/c_s \ll kc_s$. Deduce the physical behaviour of the waves and the fact that an upwards propagating wave carries energy downwards.

PROBLEM 4.7. **Entropy Waves**.
Show that, in the absence of gravity, the linearised MHD equations possess a solution with $\omega = p_1 = 0$, $\mathbf{v}_1 = \mathbf{B}_1 = \mathbf{0}$ and an arbitrary ρ_1 and entropy.

1.5 Chapter 5

PROBLEM 5.1. **Hydrodynamic Shock Wave.**
Show that the shock relations (5.14)–(5.16) for a hydrodynamic shock together with the entropy condition (5.17) imply that the Mach number exceeds unity ($M_1 \geqslant 1$).

1.6 Chapter 6

PROBLEM 6.1. **Two-dimensional X- and O-points**.
Show that any linear null with field components $B_X = bX + 2cY$ and $B_Y = -2aX + dY$ can be transformed to $B_x = B_0 y/L_0,\quad B_y = B_0\bar{\alpha}^2 x/L_0$.

PROBLEM 6.2. **Magnetic Relaxation.**
Consider the process of magnetic relaxation (Sec.**??**) of an ideal incompressible plasma satisfying the model equation of motion (6.13).
(i) Prove that the magnetic energy decreases when the Lorentz force does positive work on the plasma.
(ii) Prove Eq.(6.14), so that the total energy decreases monotonically.

PROBLEM 6.3. **Cusp-Point in a Sheared X-point field.**

Consider the field near a cusp-point in Fig.**??**e of Sec.**??**. Suppose shearing is present only in region I below the X-point, so that $B_z = 0$ in regions II and III to either side. In region I, seek a self-similar solution of the form $A = r^a f(\xi)$, where $\xi = \theta/r^b$, for which the equilibrium equation becomes $\nabla^2 A = -\epsilon A^{-n}$ and the separatrix is $\xi = 1$. In region II, seek a potential field. Show that for total pressure balance across the separatrix $a = 1 + 3b/2$ and $n = (2 + b)/(2 + 3b)$.

PROBLEM 6.4. **Diffusion of a Current Sheet.**

Prove the result (6.22) that, for a one-dimensional current sheet obeying the diffusion equation (6.21), the magnetic energy is converted continuously into heat as the magnetic field diffuses.

PROBLEM 6.5. **Advection of a One-Dimensional Magnetic Field.**

Find the effect in the limit of $R_m >> 1$ of a stagnation-point flow ($v_x = -V_0 x/a$, $v_y = V_0 y/a$) on a field that is initially $\mathbf{B} = B_0 \cos(x/a)\hat{\mathbf{y}}$ at $t = 0$ between $x = -\frac{1}{2}\pi a$ and $\frac{1}{2}\pi a$.

PROBLEM 6.6. **Magnetic Annihilation.**

Show that the stagnation-point flow (Eq.6.23) acting on a magnetic field [$\mathbf{B} = B(x)\hat{\mathbf{y}}$] satisfying Eq.(6.24) also satisfies the equation of motion and so is an exact solution of the MHD equations.

PROBLEM 6.7. **Energetics of Sweet-Parker Mechanism.**

(i) Prove the steady-state *electromagnetic energy equation* from Ohm's law and Maxwell's equations.

(ii) Deduce that half of the inflowing electromagnetic energy goes into Ohmic heating and half into the work done by $\mathbf{j} \times \mathbf{B}$.

(iii) Use the *mechanical energy equation* to show that the work done by $\mathbf{j} \times \mathbf{B}$ goes into kinetic energy when the plasma is incompressible and that the work done by $\boldsymbol{\nabla} p$ is negligible.

PROBLEM 6.8. **Quasi-Separatrix Layer.**

Calculate the norm (N) of the mapping for the sheared X-field $(B_x, B_y, B_z) = (x, -y, l)$ inside a cube.

PROBLEM 6.9. **Field-Line Conservation in Ideal MHD.**

Use the equation of mass continuity and the ideal induction equation to show that an elemental segment ($\delta\mathbf{l}$) of a line moving with the plasma obeys the same equation as $\mathbf{B}/\rho$.

PROBLEM 6.10. **Non-ideal Field Line Velocity.**

Show that for two-dimensional resistive flow there is no unique definition of field-line velocity.

PROBLEM 6.11. **Euler Potentials.**

Use Eqs.(6.74) for Euler potentials to show that line or flux conservation holds if $\mathbf{B} \times (\boldsymbol{\nabla} \times \mathbf{N}) = \mathbf{0}$ or if $\boldsymbol{\nabla} \times \mathbf{N} = \mathbf{0}$, respectively.

1.7 Chapter 7

PROBLEM 7.1 **Effect of Steady Flow on Energy Method.**

Consider a steady flow and magnetic field of the form $\mathbf{v}_0(x)$ and $\mathbf{B}_0(x)$ and show that the linearised equation of motion for perturbations of the form $\boldsymbol{\xi}(x,y,z,t) = \boldsymbol{\xi}(x)\exp i(k_y y + k_z z - \omega t)$ becomes $-\tilde{\omega}^2\rho_0\ \boldsymbol{\xi}(x) = \mathbf{F}[\boldsymbol{\xi}(x)]$, in place of Eq.(7.26), where $-\tilde{\omega} = \omega - \mathbf{k}.\mathbf{v}_0(x)$.

PROBLEM 7.2 **Rayleigh-Taylor Instability.**

Consider two incompressible, inviscid plasmas of uniform densities ($\rho_0^{(-)}$, $\rho_0^{(+)}$), separated by a horizontal boundary, with gravity acting vertically downwards. Show that, if the plasma of larger density $\rho_0^{(+)}$ rests on top of the other ($\rho_0^{(+)} > \rho_0^{(-)}$), the system is unstable with perturbations like $e^{i\omega t}$ growing at a rate $|\omega|$ given by

$$\omega^2 = -gk\left(\frac{\rho_0^{(+)} - \rho_0^{(-)}}{\rho_0^{(+)} + \rho_0^{(-)}}\right).$$

PROBLEM 7.3. **Continuously Stratified Medium.**

Consider an equilibrium horizontal magnetic field $\mathbf{B}_0 = [B_0(z), 0, 0]$ in a gravitationally stratified atmosphere, with $p_0 = p_0(z)$ and $\rho_0 = \rho_0(z)$. Linearise the inviscid, ideal, adiabatic MHD equations and assume perturbations of the form $f(x,y,z,t) = f(z)e^{i(ly-\omega t)}$. When the wavenumber l is large ($l \to \infty$), prove that the local dispersion relation is

$$\left(c_s^2 + v_A^2\right)\omega^2 = c_s^2 N^2 + g v_A^2 \frac{d}{dz}\left[\log\left(\frac{B_0}{\rho_0}\right)\right],$$

where $v_A^2 = B_0^2/\mu\rho_0$, $c_s^2 = \gamma p_0/\rho_0$ and $N^2 = (g/\gamma)d/dz[\log(p_0/\rho_0^\gamma)]$. Deduce that the plasma can be unstable ($\omega^2 < 0$) even when it is convectively stable ($N^2 > 0$).

PROBLEM 7.4. **Magnetic Rayleigh-Taylor Instability.**

Show that *incompressible* perturbations of the form $\mathbf{v}_1 = [v_x(z), 0, v_z(z)]e^{i(kx+\omega t)}$, $\rho_1 = \rho_1(z)e^{i(kx+\omega t)}$, $\mathbf{B}_1 = [B_{1x}(z), 0, B_{1z}(z)]e^{i(kx+\omega t)}$ to an interface at $z = 0$ between two uniform media (with density ρ_+ and magnetic field $B_+\hat{\mathbf{x}}$ above the interface and ρ_- and $B_-\hat{\mathbf{x}}$ below it) have dispersion relation

$$\omega^2 = \frac{k^2}{\mu}\left(\frac{B_+^2 + B_-^2}{\rho_+ + \rho_-}\right) + kg\left(\frac{\rho_- - \rho_+}{\rho_- + \rho_+}\right).$$

PROBLEM 7.5. **Sausage Instability.**

Use the Energy Method to show that a cylindrical tube in equilibrium with pressure $p_0(R)$ and magnetic field $B_{0\phi}(R)$ is unstable to perturbations of the form $\boldsymbol{\xi} = \exp i(kz + \omega t)[\xi_R(R)\hat{\mathbf{R}} + i\xi_z(R)\hat{\mathbf{z}}]$ with $\omega^2 < 0$.

PROBLEM 7.6. **Kelvin-Helmholtz Instability.**

Consider two homogeneous plasma layers with field and flow $\mathbf{v}_0^+$ and $\mathbf{B}_0^+$ in $x > 0$ and $\mathbf{v}_0^-$ and $\mathbf{B}_0^-$ in $x < 0$, having y- and z-components parallel to the interface. Show that, under an incompressible displacement of the form $\boldsymbol{\xi} \sim \exp[i(k_y + k_z z - \omega t)]$, the interface is unstable when

$$[\mathbf{k}\cdot(\mathbf{v}_0^+ - \mathbf{v}_0^-)]^2 > \frac{(\mathbf{k}\cdot\mathbf{B}_0^+)^2 + (\mathbf{k}\cdot\mathbf{B}_0^-)^2}{\mu\rho^+}\frac{\rho^+ + \rho^-}{\rho^-}, \qquad \text{where} \qquad \mathbf{k} = k_y\hat{\mathbf{y}} + k_z\hat{\mathbf{z}}.$$

1.8 Chapter 8

PROBLEM 8.1. **An Anti-Dynamo Theorem.**
Prove that a planar velocity $\mathbf{v} = v_x(x, y, z, t)\hat{\mathbf{x}} + v_y(x, y, z, t)\hat{\mathbf{y}}$ cannot produce dynamo action.

PROBLEM 8.2. **A Fast Dynamo.**
Demonstrate the stretch-fold-shear dynamo mechanism by considering the action of an ideal Beltrami flow in Cartesian coordinates [namely, $\mathbf{v} = 2\cos^2 t(0, \sin x, \cos x)$], acting for a time $t = \pi$, on a field $\mathbf{B} = (1, 0, 0)\cos kx$ in the large magnetic Reynolds limit.

PROBLEM 8.3. **Flux Expulsion.**
Consider the effect of a differential rotation $\mathbf{v} = R\Omega(R)\hat{\boldsymbol{\phi}}$ in cylindrical polars (R, ϕ, z) on a field $(B_R, B_\phi, 0)$ that is initially uniform $(B_0\hat{\mathbf{x}})$.
(a) Show that, if there is initially no diffusion and $d\omega/dR \neq 0$, then the azimuthal field (B_ϕ) grows in time, and that it reaches a value of order $R_m^{1/2}B_0$ before diffusion sets in (assuming $R_m \equiv \omega_0 R_0^2/\eta \gg 1$).
(b) Prove that, if $\Omega(R)$ is constant inside $R = R_0$ and vanishes outside, then the ultimate steady state has a vanishing field inside $R = R_0$ (by so-called *flux expulsion*).

PROBLEM 8.4. **Differential Rotation.**
Consider the effect of a toroidal velocity $\mathbf{v} = R\Omega(R, z)\hat{\boldsymbol{\phi}}$ in cylindrical polars on a poloidal field $(B_0\hat{\mathbf{z}})$, which remains steady and uniform.
(a) Show that, if there is no diffusion initially, then the toroidal field increases linearly in time and reaches a value of order $R_m B_0$ before diffusion sets in.
(b) Find the ultimate steady state when Ω is a function of $r = (R^2 + z^2)^{1/2}$ alone.

PROBLEM 8.5. **Parker Dynamo.**
Examine the properties of Parker's dynamo in Cartesian geometry (Sec.**??**) in the particular case when $B_z = 0$ and $\partial/\partial z = 0$.

1.9 Chapter 9

PROBLEM 9.1. **Linear Theory of Magnetoconvection**.
Derive the linear dispersion relation for magnetoconvection (Eq.9.4) in the Boussinesq approximation.

PROBLEM 9.2. **Convection in the Absence of a Magnetic Field**.
Use Eq.(9.4) for the case of no magnetic field with rolls $(k_y = 0)$ aligned with the y-direction, to show that convection sets in as overturning motion when $Ra > 81\pi^4/4$ at $k_x = \pi d/\sqrt{2}$, a classic result due to Rayleigh (1916) (Sec.7.5.6), which gives the precise value for the order of magnitude criterion (Eq.9.1).

PROBLEM 9.3. **Convection in a Horizontal Magnetic Field**.
Use Eq.(9.4) for the case of a horizontal magnetic field $(\mathbf{B}_0 = B_0\hat{\mathbf{x}})$ with no dissipative effects $(\kappa = \eta = \nu = 0)$. Show that rolls parallel to the field (with $k_x = 0$) are unstable $(\omega > 0)$ for all wavenumbers $k_y \neq 0$; but for a given $k_x \neq 0$, prove that convection is inhibited for all k_y if the

magnetic field is so strong that $B_0^2/(\mu\rho_0) > g\alpha_T \Delta T/(dk^2)$.

PROBLEM 9.4. **Concentration of a Flux Tube by a Stagnation-Point Flow**.

(a) By seeking steady-state solutions of the induction equation with no electric field, show that a sheet ($B\ \hat{\mathbf{y}}$) of flux $2B_0a$ is concentrated by a 2D stagnation-point flow ($v_x = -V_0x/a, v_y = V_0y/a$) with $R_m = aV_0/(2\eta)$ to the form

$$B(x) = 2B_0(R_m/\pi)^{1/2} \exp(-R_m x^2/a^2).$$

Deduce that its thickness is $2a/\sqrt{R}_m$ and its peak field strength is $2B_0\sqrt{(}R_m/\pi)$.

(b) Prove that the corresponding effect of a 3D flow ($v_R = -V_0R/a, v_z = 2V_0z/a$) in cylindrical polars on a field $B(R)\ \hat{\mathbf{z}}$ is to make $B(R) = B_0R_m \exp(-R_mR^2/a^2)$.

PROBLEM 9.5. **Shape of a Buoyant Flux Tube**.

Show that the equation for a vertical slender flux tube in equilibrium in the yz-plane between magnetic buoyancy and magnetic tension in an isothermal medium of scale-height H is given by $\cos\,[y/(2H)] = e^{(z-z_s)/(2H)}$, where $(y, z) = (0, z_s)$ is the summit of the tube. Hence deduce that the maximum footpoint separation for such a tube is $2\pi H$.

PROBLEM 9.6. **Magnetic Buoyancy Instability**.

Consider a 1D equilibrium $[p_0(z), \rho_0(z), T_0(z), B_0(z)\hat{\mathbf{x}}]$ satisfying the perfect gas law and magnetostatic balance with uniform sound and Alfvén speeds. Find the dispersion relation for perturbations of the form $f(z)e^{i(kx+ny-\omega t)}$ when $n^{-1} \ll k^{-1}, H$. Deduce that, when $0 < k^2H < -(1/B_0)dB_0/dz$, the configuration is unstable.

PROBLEM 9.7. **Self-Similar Model for a Sunspot**.

The Schlüter-Temesvary model for a sunspot has self-similar magnetic field $B_R = -\frac{1}{2}Rf(\zeta)dB_i/dz$, $B_z = f(\zeta)B_i(z)$, in terms of the similarity variable $\zeta = RB_i^{1/2}(z)$, where $f(0) = 1$. It satisfies $\boldsymbol{\nabla}\cdot\mathbf{B} = 0$ and Eqs.(9.23) for magnetohydrostatic equilibrium. Calculate the flux (F_m) through the spot and show how $B_i(z)$ and $p_e(z)$ may be determined if the temperature structure, flux (F_m) and shape factor $f(\zeta)(= e^{-\zeta^2}$, for instance) are prescribed, together with B_i and dB_i/dz at $z = 0$.

1.10 Chapter 10

PROBLEM 10.1. **Connection Formulae for Resonant Absorption**.

Consider a linear perturbation of the form $f(r)\exp[i(m\phi + kz - \omega t)]$ to a twisted cylindrical flux tube in equilibrium with field components $[B_{0\phi}(r), B_{0z}(r)]$. Such perturbations satisfy the *Hain-Lüst equation* (4.60).

(a) Show that $g_BP_1 - 2f_BB_{0\phi}B_{0z}\xi_{1r}/(\mu r)$ is conserved and equal to a constant (C_A) at the Alfvén resonance point $[\omega_A(r) = \omega]$, where $g_B = (m/r)B_{0z} - kB_{0\phi}$, $f_B = (m/r)B_{0\phi} + kB_{0z}$, $P_1 = p_1 + \mathbf{B}_0\cdot\mathbf{B}_1$ is the total pressure perturbation, and ξ_{1r} is the radial displacement perturbation.

(b) Show that the thickness of the dissipation layer is $[\omega(\nu+\omega)/|\Delta|]^{1/3}$, where $\Delta = -2\omega_Ad\omega_A/dr$.

(c) Show that the jumps in ξ_{1r} and P_1' across the resonant dissipation layer are

$$[\xi_{1r}] = -i\pi\frac{\text{sign }\omega}{|\Delta|}\frac{g_B}{\rho B_0^2}C_A,$$

$$[P_1'] = -i\pi \frac{\text{sign } \omega}{|\Delta|} \frac{2B_{0\phi}B_{0z}f_B}{\rho B_0^2 \mu r} C_A,$$

and are therefore independent of the dissipation coefficients (ν, η).

PROBLEM 10.2. **Phase Mixing of Waves in Space**.

Derive the solution of Eq.(10.32) for the form of Eq.(10.33) in the case of weak damping and strong phase mixing, namely,

$$\frac{1}{k_z} \ll 1 \quad \text{and} \quad \frac{z}{k_z}\frac{dk_z}{dx} \gg 1.$$

PROBLEM 10.3. **Phase Mixing Solution by Multiple Scales**.

Seek solutions, with $t_0 = t$, $t_1 = \varepsilon t$ and $\varepsilon \ll 1$, of Eq.(10.32) in the form

$$v_{1y} = V_{0y}(x, z, t_0, t_1) + \varepsilon V_{1y}(x, z, t_0, t_1) + ...$$

PROBLEM 10.4. **Phase Mixing of Waves in Time.**

Find the time-scale for phase mixing in time of Alfvén waves.

PROBLEM 10.5. **Interaction Distance of Photospheric Magnetic Fragments**.

Consider a 2D potential field model of two fragments of flux $\pm F_0$ at points $(x, y) = (a, 0)$ on the x-axis in an ambient uniform magnetic field $B_0\hat{\boldsymbol{x}}$. Show that:

(a) when $a > d \equiv 2F_0/(\pi B_0)$, there are two null points on the x-axis and none on the y-axis;

(b) when $a = d$, a second-order null point appears at the origin with separatrices inclined at $\pi/3$;

(c) when $a < d$, a first-order null point is present on the y-axis, and its maximum altitude is $\frac{1}{2}d$;

(d) for a 3D field the interaction distance is $d^* = \sqrt{F_0/(\pi B_0)}$.

PROBLEM 10.6. **A Smooth Force-Free Field from Imposed Footpoint Motions**.

(a) Show that the small force-free perturbation $\mathbf{B}_0 + \mathbf{B}_1$ to a uniform field $\mathbf{B}_0$ produced by arbitrary perturbations $\boldsymbol{\xi} = \boldsymbol{\xi}^-$ on the plane $z = 0$ and $\boldsymbol{\xi} = \boldsymbol{\xi}^+$ on $z = d$ is determined uniquely to be

$$\boldsymbol{\xi} = \frac{\mathbf{k}_\perp \cdot \boldsymbol{\xi}^-}{k_\perp^2} \frac{\sinh[k_\perp(d-z)]}{\sinh(k_\perp d)} \mathbf{k}_\perp + \frac{\mathbf{k}_\perp \cdot \boldsymbol{\xi}^+}{k_\perp^2} \frac{\sinh(k_\perp z)}{\sinh(k_\perp d)} \mathbf{k}_\perp$$

$$- \left(\frac{d-z}{d}\right) \frac{\mathbf{k}_\perp \times (\mathbf{k}_\perp \times \boldsymbol{\xi}^-)}{k_\perp^2} - \frac{z}{d} \frac{\mathbf{k}_\perp \times (\mathbf{k}_\perp \times \boldsymbol{\xi}^+)}{k_\perp^2},$$

where $\mathbf{B}_1 \sim \exp i(\omega t + \mathbf{k} \cdot \mathbf{r})$ and $\boldsymbol{\xi} \sim \exp i(\omega t + \mathbf{k} \cdot \mathbf{r})$.

(b) Show that the force-free currents arise from a difference in rotational motions on the boundaries.

(c) Show that force-free fields here are a low-frequency limit of shear Alfvén waves.

PROBLEM 10.7. **Current-Sheet Formation in Flux-Tube Tectonics**.

Consider a 2D (x, z) corona between two photospheres on $z = \pm L$, with an array of line sources of flux $[(2n + 1)w, \pm L]$, where $w/(2L) \ll 1$ is the aspect ratio of the loops.

(a) Prove that the initial potential magnetic field is

$$(B_{0x}, B_{0z}) = \frac{F/(2w)}{[\cosh[\pi(L - |z|)/w] + \cos(\pi x/w)]} \left(\text{sgn}(z) \sin\frac{\pi x}{w}, \sin\frac{\pi(L - |z|)}{w}\right),$$

and describe its properties.

(b) Suppose the source footpoints are sheared by $Y_n = \pm(-1)^n Y$. Show that the current density is $\mathbf{j} = (db/dA_0)\mathbf{B}_0$, where A_0 is the flux function associated with the above initial potential field $\mathbf{B}_0 = B_{0x}\hat{\mathbf{x}} + B_{0y}\hat{\mathbf{y}}$ and $b(A_0) = Y/V_0$, where

$$V_0(A_0) = \frac{4w^2}{\pi F} \log_e \frac{\sinh^2(\frac{1}{2}\pi L/w)\cos^2(\pi A_0/F) + \cosh^2(\frac{1}{2}\pi L/w)\sin^2(\pi A_0/F)}{\sin^2(\pi A_0/F)}.$$

(c) Show that the current flows in a narrow layer of width $w/\pi e^{-[\pi L/(2w)]}$.

PROBLEM 10.8. **Binary Reconnection**.

(a) If the position of one magnetic source rotates relative to another, calculate the resulting electric field and field-line velocity.

(b) Show that, if the mean photospheric flux densities of positive and negative flux are $\bar{B}_+$ and $\bar{B}_-$, then the heat flux due to the source motion (v_0) is

$$F_{heat} = \frac{\bar{B}_+^2 v_0}{3\pi\mu}.$$

1.11 Chapter 11

PROBLEM 11.1. **Generalised Kippenhahn-Schlüter Model.**

Extend the Kippenhahn-Schlüter model to allow for a small external pressure by imposing boundary conditions $p = p_e$ and $B_z = B_{ze}$ at $x = H$ and linearising about the resulting Kippenhahn-Schlüter model. Show that the horizontal field strength increases with height over a scale L_0 when $l^{1/2} \gg \alpha > 1.7$ (a thin prominence) or $\alpha^2 \gg l < 1$ (a thick weak prominence), where $l = L_0/H$ and $\alpha = 2B_{0x}/(2\mu p_e + B_{ze}^2)^{1/2}$.

PROBLEM 11.2. **Nonisothermal Kippenhahn-Schlüter Model.**

For an isothermal Kippenhahn-Schlüter model, rewrite the standard solution in terms of $\beta_1 = 2\mu p_1/B_x^2$, $H_1 = k_B T_1/(mg)$ and $p_0 = B_{z\infty}^2/(2\mu)$. Next, obtain the corresponding solution when the temperature is a given function $T(x)$ and the boundary conditions are imposed to be $p = p_1$ and $T = T_1$ at $x = \pm x_1$. Deduce that there exists a maximum allowable plasma beta (β_1) for the equilibrium to exist.

PROBLEM 11.3. **Oscillation of a Kuperus-Raadu Model.**

Show that vertical oscillations of a Kuperus-Raadu prominence model give a period of $2\pi(h/g)^{1/2}$.

PROBLEM 11.4. **Flux-Rope Model.**

Seek solutions for current-sheet support in a force-free flux rope with $B_z = cA$.

PROBLEM 11.5. **Linear Force-Free Flux-Rope Model.**

Set up a model for a cylindrical linear force-free flux rope with no axial field reversal.

PROBLEM 11.6. **A Dip in a Potential Field.**

Show that, for a 2.5D potential arcade with the fundamental solution plus the nth harmonic, inverse polarity is not possible and that a dip needs parasite polarity.

PROBLEM 11.7. **Current-Sheet Models using Complex-Variable Theory.**
Use complex-variable theory to build current-sheet models of infinite or finite height by modifying the field given by $B_y + iB_x = B_0(p^2 + z^2)^{1/2}/z$, where $z = x + iy$.

1.12 Chapter 12

PROBLEM 12.1. **Acceleration of an Isolated Horizontal Flux Rope**.
Consider an isolated line-tied flux rope of radius a with a purely poloidal field B_p at its surface. Show that the flux rope is accelerated either indefinitely or to a constant speed, depending on whether the current, radius or twist is held constant.

PROBLEM 12.2. **Instability of a Horizontal Flux Rope**.
Consider equilibria of a line-tied flux rope in a dipole background field. Prove that solutions on the lower branch of equilibria in Fig.**??**b are stable while the upper branch is unstable.

PROBLEM 12.3. **Emergence of Magnetic Flux**.
Consider a flux rope modelled as a line current (I) in the magnetic field of a line dipole at $(-d, 0)$ below the photosphere at $(-d, 0)$. Suppose new flux emerges in the form of a line dipole at $(-x_d, y_d)$. Solve Poisson's equation to find the flux function for the resulting equilibrium.

PROBLEM 12.4. **Current Sheet below an Erupting Flux Rope**.
Find the magnetic field due to a flux rope modelled as a line current (I) at height h sitting in the corona in the magnetic field of a line dipole at depth d below the photosphere. Suppose the flux rope erupts without reconnection and produces a current sheet stretching up from the photosphere to height q. Find the resulting magnetic field.

PROBLEM 12.5. **The Hoop Force of a Toroidal Flux Rope**.
Fill in the details of the proof for calculating the hoop force of a toroidal flux rope by: (a) calculating A_ϕ for a toroidal current, (b) approximating this close to the flux rope, (c) showing that the poloidal flux function $\tilde{A} = \tilde{A}_0(\hat{r}) + \tilde{A}_1(\hat{r}, \hat{\theta})$ with $\tilde{A}_1(\hat{r}, \hat{\theta}) = -\Delta(\hat{r}) B_{\hat{\theta}0}(\hat{r}) \cos\hat{\theta} \ll \tilde{A}_0$ represents a set of circular flux surfaces that are displaced by Δ, (d) finding the field on the inner surface of the flux rope, (e) finding the flux function outside the flux rope and (f) determining the free constants by matching the field at the surface of the rope.

PROBLEM 12.6. **Change of Current during Expansion of a Flux Rope**.
Fill out the details of the proof of Eq.(12.14) for the behaviour of the current (I) as a function of the major radius (R_0) of a flux ring.

PROBLEM 12.7. **Condition for Torus Instability**.
Show that, if the total magnetic flux ($F = F_{m(I)} + F_{m(ext)}$) enclosed by a toroidal flux rope (given by Eq.12.17) is held constant while both $F_{m(I)}$ and $F_{m(ext)}$ vary with R_0, then the condition for torus instability with an external field $B_{ext} = \hat{B}R_0^{-n}$ becomes $n > 3/2 - 1/(2c)$, where $c = \log_e(8R_0/a) - 1$.

PROBLEM 12.8. **Current (I) of a Toroidal Flux Rope**.
Show that $Ia = constant$ for a linear force-free toroidal flux rope of current I and radius a, whose axial flux is constant and whose axial field vanishes on its surface.

PROBLEM 12.9. **Titov-Démoulin Model**.
Show that, in the Titov-Démoulin model for the equilibrium of an active-region flux rope of current I, depth d, major radius R_0 and minor radius a, I reaches a maximum at about $R_0 \approx L/\sqrt{2}$, and torus instability sets in at about $R_0 \approx \sqrt{2}L$, when $d \ll R_0$ and $a \ll R_0$.

1.13 Chapter 13

PROBLEM 13.1. **Isothermal Static Corona.**
Find the pressure $p(r)$ and density $\rho(r)$ for an isothermal, static, spherically symmetric corona.

PROBLEM 13.2. **Effect of Depositing Heat at a Single Radius.**
Find the temperature $T(r)$ for a corona with heat conduction inward and outward from a level (r_0) where heat is deposited.

PROBLEM 13.3. **Properties of the Isothermal Solar-Wind Solution.**
Show that:
(a) in the low corona, the flow speed is 0.1–10 km s^{-1}, depending on the coronal temperature;
(b) below the critical point, the density variation is very similar to a static atmosphere; and
(c) the mass-loss rate is of the order of $10^{-14}M_\odot$ per year.

PROBLEM 13.4. **Maximum Temperature for an Isothermal Wind.**
Show that, if $T > 5.8\times10^6$ K, an isothermal wind does not exist.

PROBLEM 13.5. **Polytropic Solar Wind.**
For a spherically symmetric polytropic solar wind:
(a) find the critical-point location and deduce that $\frac{1}{2}v^2(r) + c_s^2(r)/(\alpha - 1) - GM_\odot/r = constant$;
(b) find the condition that $p \to 0$ as $r \to \infty$ for breeze solutions.

PROBLEM 13.6. **Condition for Existence of a Polytropic Solar Wind.**
Show that a polytropic solar wind with $\alpha = 1.1$ will exist if $T_0 > 1.1$ MK, but that an adiabatic wind needs $T_0 > 4.6$ MK.

PROBLEM 13.7. **Properties of a Polytropic Solar Wind.**
Show that:
(a) if $1 < \alpha < 5/3$, the critical point is a saddle point; and
(b) if $1 < \alpha < 3/2$, there is a solar-wind solution whose pressure force always dominates gravity and that changes from subsonic to supersonic as it passes through the critical point.

PROBLEM 13.8. **Properties of a Rotating Wind with Angular Speed $\Omega_\odot$.**
Show that in the equatorial plane the addition of rotation:

(a) changes Eq.(13.6) to

$$\left(v - \frac{v_c^2}{v}\right)\frac{dv}{dr} = \frac{2v_c^2}{r^3}(r^2 - r_{c0}r + \tfrac{1}{2}\tau^2 r_0^2),$$

where r_{c0} is the critical-point radius in the absence of rotation and $\tau = r_0\Omega_\odot/v_c$;

(b) gives one critical point for $r_{c0} > r_0$ when $0 < \tau < \tau_1$, two when $\tau_1 < \tau < \tau_2$ and none when $\tau > \tau_2$, where $\tau_1 = \sqrt{2}(r_{c0}/r_0 - 1)^{1/2}$ and $\tau_2 = r_{c0}/(\sqrt{2}r_0)$;

(c) and changes the solar-wind density by a small amount to be estimated.

PROBLEM 13.9. **Angular-Momentum Loss.**

Show that the time-scale for angular-momentum loss is of order the Sun's age.

PROBLEM 13.10. **Isothermal Coronal Hole.**

For an isothermal coronal hole with area function $A(r) = ar^n$, show how n affects the critical point location, and find the behaviour of the velocity and pressure at large r for the solar-wind solution.

2

Solar Ground-Based Observatories and Space Satellites

A summary is given below of ground-based telescopes at the Canary Islands, the National Solar and Big Bear Observatories (DOT, SST, VTT, THÉMIS, GREGOR, BiSON, GONG, EST, DST, MPST, ATST, NST), as well as previous, current and future space satellites (with launch dates): OSO (1962–1975), Skylab (1973), GOES (1975–), P78-1 (1979), SMM (1980), Hinotori (1981), Spacelab2 (1985), Ulysses (1990), Yohkoh (1991), CORONAS (1994, 2001, 2009), SoHO (1995), TRACE (1998), RHESSI (2002), Hinode (2006), STEREO (2006), Sunrise Balloon (2009), SDO (2010), IRIS (2013), CLASP (2014), Solar Orbiter (2017), Solar Probe Plus (2018), Solar C (2019), IHP (2021).

2.1 Ground-Based Solar Observatories

A list of large ground-based optical solar telescopes since 1900 is given in Table 2.1 and includes: KSO (Kodaikanal Solar Observatory), SST (Snow Solar Telescope), MWO (Mount Wilson Observatory), STT (Solar Tower Telescope), ET (Einsteinturm), STT (Solar Tower Telescope), MMO (McMath-Hulbert Observatory), STT (Solar Tunnel Telescope), MPST (McMath-Pierce Solar Telescope), SOT (Solar Observatory Tower at Meudon), DST (Dunn Solar Telescope), BBVR (Big Bear Vacuum Reflector), HST (Hα Spar Telescope), HDST (Hida Domeless Solar Telescope), SVST (Swedish Vacuum Solar Telescope), VTT (Vacuum Tower Telescope), THÉMIS (at Teide Observatory), DOT (Dutch Open Telescope), PVSO (Prairie View Solar Observatory), SST (Swedish Solar Telescope), ONSET (Optical and Near-Infrared Solar Eruption Tracer), NVST (New Vacuum Solar Telescope), NST (New Solar Telescope), GREGOR (at Teide Observatory), ATST (Advanced Technology Solar Telescope), EST (European Solar Telescope), COSMO (Coronal Solar Magnetism Observatory), NLST (National Large Solar Telescope), CGST (Chinese Giant Solar Telescope). Some of those I know best are described below.

(i) TENERIFE and LA PALMA

The Instituto de Astrofísica de Canarias (IAC) operates several solar telescopes in the Canary Islands. On La Palma at the Observatorio del Roque de los Muchachos, there is the DOT and SST. On Tenerife at Teide Observatory, there are nodes of BiSON and GONG and also the VTT, THÉMIS and GREGOR.

DOT (Dutch Open Telescope)
DOT has a 45 cm diameter primary mirror, built in 1997 and run by Rob Rutten. With a physically open structure, the wind blows right through the telescope, but the air at the mirror has

Table 2.1. *Large Ground-Based Telescopes*

Name	Aperture	Year	Location	Country
KSO	20 cm	1901	Kodaikanal	India
SST	61 cm	1904	Mount Wilson	USA
MWO	35 cm	1912	Mount Wilson	USA
ET	60 cm	1924	Potsdam	Germany
STT	45 cm	1930	Tokyo	Japan
MMO	61 cm	1941	Michigan	USA
STT	15 cm	1942	Göttingen	Germany
STT	61 cm	1958	Kodaikanal	India
MPST	161 cm	1961	Kitt Peak, USA	USA
SOT	60 cm	1968	Meudon, France	France
DST	152 cm	1969	Sacramento Peak	USA
BBVR	65 cm	1969	California	USA
HST	25 cm	1976	Udaipur, India	India
HDST	60 cm	1979	Takayama, Japan	Japan
SVST	47.5 cm	1985	La Palma, Spain	Swede
VTT	70 cm	1989	Tenerife, Spain	Germany
THÉMIS	90 cm	1996	Tenerife, Spain	France and Italy
DOT	45 cm	1997	La Palma, Spain	Netherlands
PVSO	35 cm	1999	Texas, USA	USA
SST	100 cm	2002	La Palma, Spain	Sweden
NST	160 cm	2008	Big Bear Lake	USA
ONSET	3×27.5 cm	2010	Yunnan, China	China
NVST	100 cm	2010	Yunnan, China	China
GREGOR	150 cm	2012	Tenerife, Spain	Germany
ATST	424 cm	planned	Hawaii, USA	USA
EST	400 cm	planned	Canary Isles, Spain	Europe
COSMO	150 cm	proposed	Hawaii, USA	USA
NLST	200 cm	proposed	Ladakh, India	India
CGST	500–800 cm	planned	West China	China

a constant temperature and so is not turbulent. Turbulence from solar ground heating is confined to a layer below the 15 m high open-tower top. The DOT's simple optical scheme permits precise optical alignment and its mechanical stability gives high pointing precision even in strong wind buffeting.

A despeckle algorithm improves the image quality by taking 100 images of the same object (e.g., a granule) with a time separation such that the atmosphere has changed drastically, but the object has not. The combination of superb imaging and speckle restoration made the DOT the first solar telescope regularly to obtain 0.2 arcsec resolution. It has six cameras working simultaneously, each with a different filter, in blue and red continua, the G band, Ca II H, narrow-band Hα and Ba II 4554.

SST (Swedish Solar Telescope)

The SST is a 1-metre vacuum refracting telescope with two modes of operation. One uses a Littrow spectrograph with a 79 grooves/mm echelle grating having a resolution of 230,000 (corresponding to 1.3 km/s at the solar surface). The other is an imaging mode, where light is split into a red and a blue beam. The red beam has a tunable filter called CRISP (CRisp Imaging SpectroPolarimeter), which operates from 510–860 nm. It measures polarization with liquid crystal modulation and a polarizing beamsplitter. The system uses three 1k×1k CCDs, two being used for direct observations and the third to aid image reconstruction.

VTT (Vacuum Tower Telescope)

The VTT is an evacuated-optics telescope operated by the Kiepenheuer Institute, Freiburg (Germany). It has a 70 cm (28 in) diameter primary mirror and a focal length of 46 metres (151 ft). It was installed in 1989, and, thanks to an adaptive optics system (in operation since 2000) it is able to resolve details down to 0.2 arcsec (150 km on the solar surface).

THÉMIS (Télescope Héliographique pour l'Étude du Magnétisme et des Instabilités Solaires)

THÉMIS is a solar telescope of 90 cm diameter, built 1996, and operated by Italy and France. It is located at Izaña, at a height of 2400 m, in the Teide Observatory. Its complex design allows for high-accuracy spectropolarimetry of the solar surface together with monochromatic high-resolution imaging.

GREGOR Solar Telescope

GREGOR is a 1.5 m telescope operated since May 2012 by a German consortium including Freiburg, Potsdam and Göttingen. The telescope is designed for high-precision measurements of the magnetic field and plasma motion in the photosphere and chromosphere with a resolution of 70 km. It is a gregorian telescope, a design invented by James Gregory, a 17th century professor of mathematics in St Andrews. Like the DOT, it is an open telescope structure with adaptive optics.

BiSON (Birmingham Solar Oscillations Network)

BiSON consists of a network of six remote solar observatories monitoring low-degree solar oscillation modes. It is operated by the High-Resolution Optical Spectroscopy group at Birmingham University and Sheffield Hallam University. BiSON has been collecting data continuously on solar oscillations since 1976, making it the longest running helioseismology network, with data covering three solar cycles.

GONG (Global Oscillation Network Group)

GONG is a community-based helioseismology program with a six-station network of velocity imagers located around the Earth for nearly continuous observations of five-minute oscillations, focusing on medium-degree modes. The stations, which became operational in 1995, are at: Big Bear Observatory (California, USA); High Altitude Observatory (Mauna Loa, Hawaii, USA); Learmonth Observatory (Western Australia); Udaipur Observatory (India); Teide Observatory (Canary Islands); and Cerro Tololo Observatory (Chile). The common instrument is a Fourier tachometer, based on a Michelson interferometer. It has a resolution of 5 arcsec and a filter that isolates the Ni I line at 6768 Å.

EST (European Solar Telescope)

EST is presently in a conceptual design study financed by the European Commission, involving 29 partners from 15 different countries. It is a 4-meter class solar telescope, to be located in the Canary Islands, optimised for studies of the magnetic coupling between the deep photosphere and upper chromosphere. This will diagnose thermal, dynamic and magnetic properties of the plasma over many scale heights, by using multiple-wavelength imaging, spectroscopy and spectropolarimetry. To achieve these goals, EST will specialize in high spatial and temporal resolution using instruments that can efficiently produce two-dimensional spectral information.

(ii) NSO (National Solar Observatory)

The National Solar Observatory of the USA operates several solar telescopes, including the Dunn Solar Telescope at Sacramento Peak near Sunspot in New Mexico, and the McMath–Pierce Solar Telescope at Kitt Peak in Arizona.

Richard B. Dunn Solar Telescope at Sacramento Peak

The Dunn Solar Telescope was originally the Vacuum Tower Telescope but was renamed in 1998. It is a unique vertical-axis solar telescope. The optical path starts at a heliostat on top of a 41-m-tall tower and travels 58.8 m underground to the primary mirror. It then returns to one of six quartz optical windows in the floor of an optical laboratory at ground level. The optics are evacuated to eliminate distortion by convective turbulence. Image derotation is undertaken by allowing the whole 100-metre-long telescope and 12-m-diameter optics lab, weighing 250 tons, to rotate, suspended from a mercury float bearing at the top of the tower.

ROSA (Rapid Oscillations in the Solar Atmosphere)

ROSA is a solar imager installed at the Dunn Solar Telescope and developed by Queen's University, Belfast. It observes the Sun simultaneously in six bandpasses in the photosphere and chromosphere with resolution 0.1 arcsec over a field of view of 60×60 arcsec. It provides movies of the magnetic field, G-band intensity, Ca II K and Hα.

McMath–Pierce Solar Telescope at Kitt Peak National Observatory

This is a 1.6 m reflecting telescope at Kitt Peak National Observatory in Arizona, USA. Built in 1962, it is the largest telescope of its kind in the world. It contains a heliostat at the top of the main tower which focuses the Sun's light down a long diagonal shaft and continues underground, where the telescope's primary mirror is located. The theoretical resolution is 0.07 arcsec, although atmospheric distortions degrade the image quality. The third mirror of the main telescope sends the light down into the observing room to two vacuum spectrographs, which are able to rotate to compensate for the rotation of the image caused by the heliostat.

ATST (Advanced Technology Solar Telescope)

The open principle of the DOT has been scaled up for the ATST, which is a large domed telescope that is planned to be built by the National Solar Observatory on the Hawaiian island of Maui. The ATST enclosure will house an off-axis gregorian telescope of diameter 4 meters. It will have a spatial resolution of 0.023 arcsec at 400 nm.

(iii) NST (New Solar Telescope) at Big Bear Solar Observatory

The observatory is located on Big Bear Lake about 75 miles east of downtown Los Angeles in California, built by Hal Zirin at Caltech in 1969 and transferred to New Jersey Institute of Technology in 1997. The lake cools the air and reduces the turbulence from solar ground heating. Originally, there was a 65 cm vacuum reflector, but in 2008 it was replaced by the NST, which is a 1.6 m clearaperture, open-frame, gregorian telescope, able to resolve solar features less than 50 km across.

2.2 Solar Space Satellites

The first satellites to observe the Sun were NASA's Pioneers 5–9, launched between 1959 and 1968, which studied the solar wind and magnetic field. In the 1970's, two Helios spacecraft and the Skylab Apollo Telescope Mount gave new data on the solar wind and solar corona, including the discovery of coronal mass ejections and coronal holes. In 1980, the Solar Maximum Mission was launched by NASA to observe γ-rays, X-rays and UV radiation from solar flares. Launched in 1991, Japan's Yohkoh satellite observed the corona for a whole solar cycle, and later Hinode (2006) provided much more detail on its dynamics.

One of the most comprehensive solar missions was SoHO (Solar and Heliospheric Observatory), launched in 1995 to provide a continuous view of the Sun from its location at the Lagrangian point between the Earth and the Sun. A follow-on mission, the Solar Dynamics Observatory (SDO), was launched in Feb 2010. Complementary observations have been obtained from out of the plane of the ecliptic by Ulysses, launched in 1990 to study the Sun's polar regions, and by the pair of STEREO spacecraft, launched in 2006 to produce stereoscopic solar images.

In future, Solar Orbiter is an ESA/NASA mission due to be launched in Jan 2017, Solar Probe Plus is a NASA mission due for launch in 2018, and Solar C is the next Japanese mission due for 2019. Solar instruments on the main space satellites are listed in Table 2.2.

OSO (Orbiting Solar Observatories) (1962 – 1978)

Early in the space programme, NASA Goddard organised a series of OSO satellites, designed to observe the Sun in UV, X rays, and γ-rays. The first in the series (OSO-1) was launched on 7 March, 1962 and the final one (OSO-8) in June 1975. The satellites included a spinning component at 15 rpm to provide pointing stability plus a de-spun platform to carry the instruments pointing at the Sun.

Skylab (14 May, 1973 – 11 July, 1979)

As part of the Apollo program, Skylab was the first space station. Three crews of three men each visited the station in 1973 and 1974, with their missions lasting 28, 59, and 84 days. They tended the instruments and returned the film used to record the images. The Apollo Telescope Mount on Skylab included eight solar experiments:

S-020 (an X-ray and EUV imager);
S-052 (a white-light coronagraph for studying the outer corona);
S-054 X-ray (a spectrograph for the outer corona);
S-055 (a UV spectroheliometer for the chromosphere and transition region);
S-056 (an X-ray telescope for the low corona);
S-082A and S-082B (EUV and UV spectroheliographs for the chromosphere and transition region);
and two hydrogen-alpha telescopes.

GOES (Geostationary Operational Environmental Satellites) (1975 –)

These are a series of satellites in geostationary orbit that provide continuous monitoring of the Earth and near-Earth space environment. Operated by NOAAA, they lie close to the equatorial plane at a speed matching the Earth's rotation, so that they hover over one position on the Earth's surface at an altitude of 35,800 km. GOES-1 was launched in 1975. Their payload includes:

Table 2.2. *Solar Space Satellites.*

Satellite	Launch	Instruments			
OSO	1962–				
SKYLAB	1973	S-020 S-056	S-052 S-082A	S-054 S-082B	S-055
GOES	1975–	XRS	EPS	MAG	SXI
P78-1	1979	BCS	SSH	XPS	WLC
SMM	1980	UVSP HXIS	ACRIM GRS	XRP CP	HXRBS
Hinotori	1981	SXT SGR	SOX PXM	HXM IMP	FLM PEM
Spacelab2	1985	SOUP XRT	CHASE	HRTS	SUSIM
Ulysses	1990	VHM EPAC	SWOOPS HISCALE	SWICS COSPIN	URAP SCE
Yohkoh	1991	HXT	SXT	WBS	BCS
Coronas	1994–	RES-K	SUVR	DIFOS	
SoHO	1995–	GOLF CDS CEILAS	VIRGO EIT COSTEP	SOI UVCS ERNE	SUMER LASCO SWAN
TRACE	1998				
RHESSI	2002				
Hinode	2006–	SOT	EIS		XRT
STEREO	2006–	SECCHI	SWAVES	IMPACT	PLASTIC
Sunrise	2009–	CWS	SUFI	IMaX	
SDO	2010–	AIA	EVE	HMI	
IRIS	2013				
CLASP	2014				
Solar Orbiter	2017?	SWA PHI SoloHI	EPD EUI METIS	MAG SPICE	RPW STIX
Probe Plus	2018?				
Solar C	2019?	SUVIT	LEMUR	XIT	
IHP	2021?				

XRS (X-ray Sensor) – an ion chamber providing whole-Sun X-ray fluxes in 0.5–4 and 1–8 Å bands, so as to detect the start, evolution and hardness of flares;

EPS (Energetic Particle Sensor) – for proton, α-particle, and electron fluxes;

A magnetometer to measure the three components of the Earth's magnetic field;

SXI (Soft X-ray Imager) producing X-ray images of the solar disc every minute at 6–60 Å since the launch of GOES-12 in 2001.

P78-1 (24 Feb, 1979 – 13 Sept, 1985)

Built using flight spares from OSO-7, this OSO-type satellite included Bragg crystal spectrometers covering 1.82–8.53 Å, a spectrometer/spectroheliometer (3–25 Å), X-ray proportional-counter spectrometers (1–250 keV) and a white-light coronagraph. The mission made the first observations of a halo coronal mass ejection, discovered the link between mass ejections and interplanetary shocks, and observed chromospheric evaporation by its effect on X-ray line profiles.

SMM (Solar Maximum Mission) (14 Feb, 1980 – 2 Dec, 1989)

SMM studied solar flares by imaging and spectroscopy in UV, EUV and X-rays. It was three-axis stabilised, so that the instruments pointed at the Sun with arcsec accuracy. The satellite suffered a malfunction in Jan 1981, but was recovered and serviced by the Space Shuttle in April 1984. Its instruments included the following.

UVSP (Ultraviolet Spectrometer and Polarimeter) measured UV radiation from flares, active regions and prominences, acquiring images in four spectral positions as it scanned across the Sun. A rotating polarizer was used to measure magnetic fields.

ACRIM (Active Cavity Radiometer Irradiance Monitor) was a pyrheliometer to monitor total solar irradiance (TSI) between 0.2 and 50 microns every 2 min. TSI was integrated over the 96-min orbital period and daily means were calculated.

XRP (soft X-Ray Polychromator) included the FCS (Flat Crystal Spectrometer) and the BCS (Bent Crystal Spectrometer), which provided photon counting rates at selected X-ray wavelengths in 1.4–22.5 Å and built up solar images.

HXRBS (Hard X-Ray Burst Spectrometer) studied hard X-ray spectra of flares on time-scales as short as 10 ms. It recorded pulse height spectra in 15 channels (25–500 keV) with a time resolution of 128 ms.

HXIS (Hard X-ray Imaging Spectrometer) obtained images over small areas in six energy bands (3.5–30 keV) with a spatial resolution of 8 arcsec and temporal resolution of 1.5–8 sec.

GRS (Gamma-Ray Spectrometer) had three detector systems that measured the spectra of flare X-rays and γ-rays over the ranges 10–140 keV for hard X-rays, 10–140 MeV for γ-rays and above 20 MeV for neutrons.

CP (Coronagraph Polarimeter) used multiple internal and external occulting discs to block out the direct light from the Sun's photosphere. The field of view was 1.6–4.1 $R_\odot$ at the sides and just over 6.0 $R_\odot$ along the diagonals. Spatial resolution was 6 arcsec for images taken in 1980 and 12 arcsec following repair in 1984.

Hinotori (Japanese for *Phoenix*) (21 Feb, 1981 – 11 July, 1991)

This Japanese satellite studied flares during solar maximum with 8 instruments:

SXT (Solar flare X-ray Telescope) imaged flare X rays in the range 10–40 keV, using rotating modulation collimators and found footprint brightening;

SOX (soft X-ray Bragg spectrometer) performed spectroscopy of X-ray emission lines from highly ionised iron in flares in the range 1.7–2.0 Å;

HXM (soft X-ray Monitor) and FLM (FLare Monitor) recorded the time profile and spectrum of X-ray flares in the range 2–20 keV;

SGR (Solar Gamma-Ray) monitored the range 0.2–9.0 MeV;

PXM (Particle X-ray Monitor) measured electron flux above 100 keV;

IMP (Instrument to Measure Plasma electron density);

PEM (Plasma Electron temperature Measurement instrument).

Spacelab2 (29 July – 6 Aug, 1985)

Spacelab2 had 5 instruments from Birmingham, Lockheed, NRL, RAL and MSSL:

XRT (X-ray telescope) – the first to image the Sun from orbit at 2.5–25 keV;

SOUP (Solar Optical Universal Polarimeter) observed the strength, structure, and evolution of magnetic fields in the photosphere between 510 and 660 nm;

SUSIM (Solar Ultraviolet Spectral Irradiance Monitor) measured UV spectral irradiance over 120–400 nm and to determine variations in the total ultraviolet flux;

HRTS (High Resolution Telescope and Spectrograph) provided images and spectra of the chromosphere and corona over the range 117–170 nm;

CHASE (Coronal Helium Abundance Spacelab Experiment) was a grazing incidence spectrograph over 15–135 nm, which determined helium abundance, as well as coronal temperature, density and composition.

Ulysses (6 Oct, 1990 – 30 June, 2009)

Ulysses was a joint ESA/NASA mission, which observed the Sun from all latitudes. (One of the original two spacecraft was cancelled by NASA in 1981.) It was powered by an RTG (Radioisotope Thermoelectric Generator) rather than solar cells and used an encounter with Jupiter to bring it out of the ecliptic, so as to perform an orbit with aphelion 5 AU and perihelion 1 AU. It made three passes of the south and north poles in 1994–1995, 2000–2001 and 2007–2008.

Ulysses had 11 instruments: Magnetometer (VHM/FGM); Solar Wind Plasma Experiment (SWOOPS); Solar Wind Ion Composition Instrument (SWICS); Unified Radio and Plasma Wave Instrument (URAP); Energetic Particle Instrument (EPAC); Low-Energy Ion and Electron Experiment (HISCALE); Cosmic Ray and Solar Particle Instrument (COSPIN); Solar X-ray and Cosmic Gamma-Ray Burst Instrument (GRB); Dust Experiment (DUST); Coronal-Sounding Experiment (SCE); Gravitational Wave Experiment (GWE).

Yohkoh (Japanese for *Sunbeam*) (30 Aug, 1991 – 14 Dec, 2001

Yohkoh was a three-axis stabilized observatory-type satellite in a nearly circular Earth orbit. It was a Japanese-UK-USA mission whose payload comprised two imagers and two spectrometers. Yohkoh suffered a spacecraft failure in Dec 2001 when the spacecraft lost pointing during the solar eclipse of Dec 14th.

HXT (Hard X-ray Telescope) was a multi-grid synthesis instrument with spatial resolution 7 arcsec, operating in the 20–100 keV range.

SXT (Soft X-ray Telescope) used grazing-incidence optics to achieve 4 arcsec spatial resolution, operating in the 0.1–4 keV range with 1024×1024-pixel CCDs.

WBS (Wide Band Spectrometer) was a continuum spectrometer for X-rays and γ-rays from 3 keV to 20 MeV (also sensitive to neutrons).

BCS (Bragg Crystal Spectrometer) spanned a wavelength range incorporating the X-ray lines Fe XXV, Fe XXVI, Ca XIX, and S XV.

CORONAS (Complex Orbital Observations Near-Earth of Activity of the Sun)

The Russian CORONAS project included three missions.

CORONAS-I was launched on 2 March, 1994 during solar minimum and carried 12 instruments including the Terek spectroheliometer, the RES-K X-ray spectrograph, the Helikon γ-ray detector, the SUVR-SP-C ultraviolet radiometer, and the DIFOS optical photometer.

CORONAS-F was launched on 31 July, 2001 near solar maximum and re-entered on 6 Dec 2005. It carried 18 instruments including UV, EUV, X-ray, and γ-ray spectrometers, radio receivers, and particle counters

CORONAS-PHOTON was launched on 29 Jan, 2009, but it developed power system problems six months after launch and two months later contact was lost. It carried an array of 12 instruments to detect UV, X-rays, γ-rays and charged particles and included three Roentgen telescopes from India.

SoHO (Solar and Heliospheric Observatory) (2 Dec, 1995 –)

SoHO has given an uninterrupted view of the Sun from a halo orbit at the Earth-Sun L1 Lagrangian point. It is a joint ESA-NASA project and remains operational in 2013, although several instruments have ceased making observations.

Its 12 instruments include 3 for helioseismology (GOLF, VIRGO and SOI), 6 for remote sensing of the Sun (CDS, EIT, LASCO, UVCS, SUMER, SWAN), and 3 for in situ measurements of the solar wind (CELIAS, COSTEP, ERNE).

CDS (Coronal Diagnostic Spectrometer) includes normal and grazing incidence spectrometers to cover several wavelength bands (31 nm–79 nm) with time resolution down to 1 s. Spatial resolution is 2 arcsec over a field of view of 4 arcmin.

CELIAS (Charge, Element, and Isotope Analysis System) studies the solar wind density and composition and energetic particles. It consists of three different particle sensors plus a fourth to monitor the absolute EUV flux from the Sun.

COSTEP (COmprehensive SupraThermal and Energetic Particle) detects very energetic electrons and ions over the range 40 keV/particle to 500 MeV/nucleon.

EIT (EUV Imaging Telescope) makes full-Sun observations in the low corona and transition region using narrow-band filters in spectral bands centred at 17.1 nm (Fe IX), 19.5 nm (Fe XII), 28.4 nm (Fe XV), and 30.4 nm (He II). Spatial resolution is about 4 arcsec and temporal resolution typically 12 minutes.

ERNE (Energetic and Relativistic Nuclei and Electrons) measures the energy spectra of elements in the range $Z = 1$–30, the abundance ratios of isotopes and the anisotropy of the particle flux.

GOLF (Global Oscillation at Low Frequencies) uses resonant scattering of sodium lines to measure the velocity and magnetic field for the full solar disc (spatially unresolved) with high sensitivity (< 1 mm/s and 1 milligauss).

LASCO (Large Angle and Spectrometric Coronagraph) carries three nested coronagraphs (C1, C2, and C3) that image the solar corona from 1.1–30 $R_\odot$ (C1: 1.1–3; C2: 1.5–6; C3: 3–30 $R_\odot$). C1 failed after loss of contact in 1997. C2 and C3 are externally occulted and have resolutions of 20 arcsec for C2, and 110 arcsec for C3.

MDI/SOI (Michelson Doppler Imager/Solar Oscillations Investigation) measures line-of-sight photospheric velocity at a million points a minute and produces maps for helioseismology. It also measures the line-of-sight magnetic field. Full-disc or magnified images have 4 or 1.2 arcsec resolution. Time resolution is 24–60 sec. The instrument uses narrow-wavelength filters centred on the 676.8 nm Ni I line.

SUMER (Solar Ultraviolet Measurements of Emitted Radiation) – a far UV spectrometer working in the 50–160 nm range, with 1 arcsec resolution, spectral resolving power ($\lambda/\Delta\lambda$) of 30,000, and time resolution better than 10 s. It produces flows, temperature and density from the chromosphere to inner corona.

SWAN (Solar Wind ANisotropies) investigates the latitude distribution of the solar wind by mapping Lyman alpha emission. It looks away from the Sun and measures the hydrogen blowing into the solar system from interplanetary space. The instantaneous field of view is 5×5 degrees, and spectral resolution is 0.001 nm.

UVCS (UltraViolet Coronagraph Spectrometer) – an occulted telescope and spectrometer with three sections enabling measurements of the line profile of H I Lyman alpha (114.8–128.3 nm), line intensity of O VII (103.2 nm), and polarised radiance of the visible corona. The field of view is 141×40 arcsec between 1.3 and 12 $R_\odot$.

VIRGO (Variability of Solar Irradiance and Gravity Oscillations) consists of two active cavity radiometers to measure total solar irradiance, and Sun photometers to measure spectral irradiance at three wavelengths (335, 550 and 865 nm).

TRACE (Transition Region and Coronal Explorer) (2 April, 1998 – 21 June, 2010)

TRACE is a high-resolution UV and EUV imager of the corona and transition region on a NASA Small Explorer (SMEX) mission. Spatial resolution is 1 arcsec (750 km) and the time cadence is as low as 1 sec in UV and 10 sec in EUV.

It observes in broadband white light and in six wavelength bands, three centred in UV (1500 Å, 1550 Å, 1600 Å) and three in EUV (171 Å, 195 Å, 284 Å). The most common observations are in 1600 Å (at $4\text{–}10\times10^3$ K), in 171 Å (Fe IX/X at 1 MK) and in 195 Å [Fe XI/XII at 1.5 MK plus flare plasma (Fe XXIV) at 15 MK]. The field of view is 8.5×8.5 arcmin.

RHESSI (Ramaty High Energy Solar Spectroscopic Imager) (5 Feb, 2002 –)

RHESSI is a NASA Small Explorer (SMEX) mission to study solar flares through X-ray and γ-ray imaging spectroscopy, covering the energy range 3 keV–17 MeV with spectral resolution 1–5 keV. Fourier-transform imaging via 9 rotating modulation collimators (grid pairs) provides spatial resolution of 2 arcsec up to 100 keV, 7 arcsec up to 400 keV and 36 arcsec above 1 MeV, while the best temporal resolution is tens of millisec for a basic image and 2 sec (half a rotation) for a detailed image. RHESSI provided the first γ-ray images of a solar flare in the 2.2 MeV neutron capture line.

Hinode (Japanese for *Sunrise*) (22 Sept 2006, –)

Hinode is a joint Japan/UK/US mission that carries three instruments.

SOT (Solar Optical Telescope) – a 50 cm aperture telescope and focal plane package that measures the photospheric vector magnetic field, as well as dynamics of the photosphere and chromosphere. SOT provides a seeing-free series of diffraction-limited images (0.2–0.3 arcsec) in the 388–668 nm range.

XRT (X-ray Telescope) is a high-resolution grazing incidence telescope, imaging coronal plasmas from 1–20 million K with 2 arcsec resolution (1 arcsec pixels). It observes different temperatures using nine X-ray filters. Field of view is 35×35 arcsec.

EIS (EUV Imaging Spectrometer) is a scanning EUV spectrograph in a normal incidence layout, covering 170–210 Å and 250–290 Å. It has two narrow slits (1 and 2 arcsec) and two wide slots

(40 and 266 arcsec), which allow 2D EUV images to be made in a raster observation. EIS spatial resolution is 2 arcsec along the slit/slot and the field of view is 360×512 arcsec.

STEREO (Solar TErrestrial RElations Observatory) (25 Oct, 2006 –)

The NASA STEREO mission reveals the 3D structure of the corona and coronal mass ejections. It consists of two nearly identical observatories, one (STEREO-A) ahead of Earth in its orbit, the other (STEREO-B) trailing behind. They were launched together and used a gravity assist from the moon to slingshot the spacecraft into a heliocentric orbit. The two spacecraft drifted away from Earth at about 22.5 degrees per year. After two years they were 90 degrees apart. Each of the two spacecraft have four instrument packages.

SECCHI (Sun Earth Connection Coronal and Heliospheric Investigation) has four instruments: an extreme ultraviolet imager (EUVI at a spatial resolution of 2 arcsec), two white-light coronagraphs [COR1 for the inner corona (1.4–4 $R_\odot$) and COR2 for the outer corona (2–15 $R_\odot$)] and a heliospheric imager (HI for 12–318 $R_\odot$).

SWAVES is an interplanetary radio burst tracker that traces the generation and evolution of travelling radio disturbances from the Sun to the orbit of Earth.

IMPACT (In-situ Measurements of Particles and CME Transients) provides the 3D distribution and properties of energetic particles and the local magnetic field.

PLASTIC (PLAsma and SupraThermal Ion Composition) provides plasma characteristics of protons, α particles, and heavy ions. It measures the mass and charge state composition of heavy ions.

Sunrise (June, 2009, ...)

The Sunrise balloon-borne observatory includes a 1m aperture gregorian telescope, a UV filter imager and an imaging vector polarimeter. The first science flight on 8–14 June, 2009 was from northern Sweden to Canada. It yielded high-quality data on the structure, dynamics and evolution of photospheric convection, oscillations and magnetic fields at a resolution of around 100 km from its three instruments:

CWS (Correlating Wavefront Sensor) is a CCD camera with 1 kHz read-out to generate images necessary for image stabilization and proper alignment;

SUFI (Sunrise Filter Imager) observes the Sun in five distinct wavelengths (214, 300, 312, 388 and 397 nm) on a 2048×2048 pixel CCD, through a filter wheel;

IMaX (Imaging Magnetograph eXperiment) observes the Zeeman splitting of the iron line (FeI) around 525 nm. The field of view is 50×50 arcsec.

SDO (Solar Dynamics Observatory) (25 Oct, 2006 –)

SDO studies the dynamics of the solar atmosphere with the following payload.

AIA (Atmospheric Imaging Assembly) images the Sun's full disc in 10 wavelengths every 10s. It has three UV-visible (1600, 1700 Å and white light) and seven EUV channels (94, 131, 171, 193, 211, 304, 335 Å), which provide coronal temperature maps from 1–20 MK, at the temperatures indicated in Table 2.3. The field of view is greater than 41 arcmin (1.28 solar radii in the EW and NS directions), and the pixel size is 0.6 arcsec.

HMI (Helioseismic and Magnetic Imager) is an improved version of MDI, which studies photospheric oscillations and magnetic field. It observes the full solar disc in the Fe I at 6173 Å with a resolution of 1 arcsec. HMI includes a refracting telescope, a narrow-band tunable filter and two 4096-pixel

Table 2.3. *Temperatures in SDO/AIA Channels*

AIA Wavelength	Characteristic Temperature
1700 Å	5000 K
1600 Å	10^5 and 5000 K
304 Å	5×10^4 K
171 Å	6.3×10^5 K
193 Å	1.2×10^6 and 2×10^7 K
211 Å	2×10^6 K
335 Å	2.5×10^6 K
94 Å	6.3×10^6 K
131 Å	4×10^5 K and 10^7 K and 1.6×10^7 K

CCD cameras. It provides Dopplergrams (maps of solar surface velocity), continuum filtergrams (broad-wavelength photospheric photographs), and line-of-sight and vector magnetograms.

EVE (EUV Variability Experiment) measures EUV irradiance with high spectral resolution, temporal cadence, and precision. It consists of: MEGS (Multiple EUV Grating Spectrograph), two grating spectrographs that measure the 5105 nm spectral irradiance with 0.1 nm spectral resolution and 10 sec cadence; MEGS-SAM, a pinhole camera to measure individual X-ray photons in the 0.17 nm range; MEGS-P, a photodiode to measure Lyman alpha emission.

ESP (EUV SpectroPhotometer) is a transmission grating with 4 bands covering 0.1–7 and 17–38 nm. It provides calibration for MEGS and 0.25 sec cadence.

IRIS (Interface Region Imaging Spectrograph) (June, 2013) .

IRIS is a NASA is a Small Explorer (SMEX) mission to study the dynamics of the chromosphere and transition region. It is in a polar synchronous orbit at an altitude of 620–670 km that allows for eight months of continuous observations per year. The telescope structure is similar to SDO except that it carries one telescope instead of four. The instrument is an imaging spectrograph that images material between 5000 K and 65,000 K (and up to 10^7 K during flares). It captures a new image every 5–10 sec and spectra every 1–2 sec. It resolves features as small as 240 km in size with a small field of view.

CLASP (Chromospheric Lyman-Alpha Spectro-Polarimeter) (2014)

CLASP is a sounding rocket experiment proposed by an international team formed by USA, Japan and some European countries. Its goal is to measure the linear polarization of the hydrogen Ly-alpha line (121.567 nm), produced by anisotropic optical pumping in the chromosphere-corona transition region, and from this observable to try to constrain via the Hanle effect the strength and orientation of the magnetic field in the upper solar chromosphere. Launch will be attempted around December 2014 from a NASA sounding rocket. The instrument consists of a far-UV Cassegrain telescope, a rotating 1/2-wave plate, a dual-beam spectrograph assembly with a grating working as a beam splitter, and an identical pair of reflective polarization analyzers each equipped with a CCD camera.

Solar Orbiter (SolO) (? 2017)

Solar Orbiter is under development by the European Space Agency (ESA). The main mission scenario is an Atlas V launch from Florida in Jan 2017. SolO is intended to perform detailed measurements of the inner heliosphere and nascent solar wind, together with close observations of the polar regions of the Sun. It will do so from an eccentric orbit moving as close as 45 $R_\odot$, or 0.21

AU, placing it inside Mercury's perihelion of 0.31 AU.

Heliospheric in-situ instruments:
SWA (Solar Wind Analyser) to measure solar wind properties and composition;
EPD (Energetic Particle Detector) to measure electrons from few keV/nuc to relativistic, protons up to 100 MeV and heavy ions up to 200 MeV/nuc;
MAG (Magnetometer) to provide detailed measurements of the magnetic field;
RPW (Radio and Plasma Wave analyser) to measure magnetic and electric fields.

Solar remote-sensing instruments:
PHI (Polarimetric and Helioseismic Imager) for the photospheric magnetic field;
EUI (EUV full-Sun and high-resolution Imager) for the solar atmosphere;
SPICE (EUV spectral Imager) for spectral imaging of the solar disc and corona;
STIX (X-ray spectrometer/telescope) for imaging spectroscopy from 4 to 150 keV;
METIS (Coronagraph) for UV (121.6 nm) and polarized visible coronal imaging;
SoloHI (Heliospheric Imager) to image steady and transient solar wind flow.

Solar Probe Plus (? 2018)

Solar Probe Plus is a planned NASA spacecraft to probe the outer corona of the Sun. It will approach to within 8.5 $R_\odot$ (0.034 AU or 6000 Mm, roughly 1/8 of the perihelion of Mercury) of the solar surface. The launch date is currently 2018.

To cancel the orbital angular momentum of the probe launched from Earth, the trajectory uses multiple gravity assists at Venus, to decrease incrementally the orbital perihelion to 8.5 $R_\odot$. The mission survives the harsh environment near the Sun, where the incident solar intensity is approximately 520 times normal by using a solar shield, made of reinforced carbon-carbon composite. As the probe passes around the Sun, it will achieve a velocity of up to 200 km/s, making it the fastest man-made object ever, almost three times faster than Helios II.

Solar-C (? 2019)

This is the next Japanese solar mission following Hinotori, Yohkoh (Solar-A) and Hinode (Solar-B), scheduled for launch in 2019. It will make high spatial resolution, high-throughput, high-cadence spectroscopic, polarimetric and X-ray observations from photosphere to corona. A major objective is to determine the role of the magnetic field in the heating and dynamics of the solar atmosphere.

The instruments will be:

SUVIT (Solar UV-Visible-IR Telescope) is a 1.5 m telescope that measures magnetic fields in the photosphere and chromosphere at 280–1100 nm. It has a spatial resolution 0.1–0.2 arcsec, a field of view of 180×180 arcsec and a time-resolution of 0.1–1 sec for imaging and 1–20 sec for spectropolarimetry.

EUVS/LEMUR (EUV/FUV High Throughput Spectroscopic Telescope) makes high-resolution spectroscopic observations of the chromosphere and corona over 17–128 nm with a field of view 280×300 arcsec. Time resolution is $<$ 10 secs at a spatial resolution of 0.28 arcsec and $<$ 1 sec at 1 arcsec.

XIT (X-ray Imaging Telescope) makes spectroscopic imaging observations of high-temperature plasma in the corona and solar flares. It has two parts. XIT-PC (Photon Counting Imaging Spectroscopy Soft X-ray Telescope) combines grazing incidence optics with a photon counting detector at a spatial resolution of 1–2 arcsec, time resolution of 10 sec and field of view 80×400 arcsec at 0.5–5 keV. XIT-NI (Ultra High Spatial Resolution Normal Incidence EUV Telescope) provides coronal imaging at 9–21 nm with a field of view 400×400 arcsec, a spatial resolution of 0.2–0.3 arcsec and a time resolution < 10 sec.

IHP (InterHelioProbe) (? 2021)

IHP is a Russian project similar to Solar Orbiter and planned for launch in 2020–2022. In one version it will consist of two spacecraft, one equatorial and the other polar. Using Venus flybys, it will approach to within about 40 $R_\odot$ of the Sun. For about 7 days it will rotate synchronously with the Sun. Solar instruments will include an X-ray telescope, and X-ray spectrometer, a magnetograph, a coronagraph and a white-light photometer, and there will also be a set of heliospheric instruments.

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