• The record of auroral observations dates back thousands of years to Greek and Chinese documents.

• The name aurora borealis (Latin for northern dawn) was coined in 1621 by P. Gassendi during a spectacular event observed in southern France.

• The aurora is mainly caused by excitation due to precipitating electrons and ions. Auroras typically are found at high geomagnetic latitudes where magnetospheric and solar wind electrons can readily access the upper atmosphere.

• Typically $10^{11} \text{Js}^{-1}$ is required to maintain auroral emissions.
• Auroral emissions are primarily due to a two-step process in which precipitating energetic auroral particles collide with the atoms and molecules of the Earth’s upper atmosphere.
  – Part of the particles kinetic energy is converted into energy stored in the chemically excited states of atmospheric species
  – The excited states relax giving off photons

• The brightest visible feature of the aurora, the green line at 557.7nm is due to the transition of an electron from $^1S$ excited state to the $^1D$ state of atomic oxygen.

• Another commonly observed line particularly in the polar cusp and cap is the red line at 639 nm. This occurs as the $^1D$ state relaxes to the ground state ($^3P_2$).

\[ O(^3P) + e \rightarrow O(^1S) + e' \]
followed by
\[ O(^1S) \rightarrow O(^1D) + h\nu \ (557.7\text{nm}) \]
or
\[ O(^1S) \rightarrow O(^3P) + h\nu \ (297.2\text{nm}) \]

For the red doublet
\[ O(^3P) + e \rightarrow O(^1D) + e' \]
followed by
\[ O(^1D) \rightarrow O(^3P) + h\nu \ (630/636.4\text{nm}) \]
($e'$ has less energy than e)

• If the O($^1S$)-state electron gives up its full energy in a single step, instead of two, it emits a 297.2 nm photon.
• The line at 557.7 nm is called a forbidden line.
  – Allowed transitions occur much more rapidly (10^{-7}s) than forbidden transitions (0.8s in this case).
  – Forbidden transitions occur at high altitudes (>200km) since at lower altitudes they have a good chance of being knocked out of the state before they can emit.

• There are many permitted oxygen and nitrogen lines from higher excited states.

• Violet N_2^+ bands at 391.4nm and 427.8nm also are intense.
• Protons (1-100 KeV) also produce aurora although generally it is much weaker than electron aurora.
  – Proton aurora is also usually observed equatorward of electron aurora.
  – In addition to exciting atmospheric atomic and molecular transitions, protons also excite emission lines in \( H_{\alpha} \)
    \[ X + H^+ \rightarrow X^+ + H^* \]
    followed by the auroral emission
    \[ H^* \rightarrow H + \nu \]
  – The hydrogen atom again collides
    \[ H + X \rightarrow H^+ + X + e_n \]
    and the process repeats. The fast atom has almost the same velocity and direction as the original proton.
  – Proton auroras are more diffuse than the incident protons.

• During the recovery phase of magnetic storms stable auroral red (SAR) arcs can form. These occur at lower latitudes and are caused by ambient electrons in the high energy tail of the thermal distribution (>3000K).
• The aurora appears as a luminous cloud with an apparent surface brightness.  
  – This is misleading since the brightness is proportional to the integrated emission per unit volume along the line of sight.  
  – If the surface brightness \( I \) is measured in photons/(cm\(^2\)s steradian), then \( 4\pi I \) represents the total emission in photons/cm\(^2\)s integrated along the line of sight.  
  – The unit for \( 4\pi I \) is the rayleigh (R). One R is \( 10^6 \) photons/cm\(^2\) s.

• During active periods the auroral luminosity can reach several hundred kilorayleighs.

• About \( 10^{-3} \)W m\(^{-2}\) is input to the atmosphere in a moderate aurora (a typical arc needs \( 10^6 \)kW or the output of a large power plant).
• The 630nm emission forms the diffuse background radiation in which the discrete arcs are embedded.

• “Blood-red” auroras are produced by low-energy electrons (<<1 keV)

• “Blood-red” auroras dominate high altitudes (>200km)

• “Red lower borders” indicate the presence of energetic particles (>10keV).

• Most auroras are yellow-green but sometimes appear gray (because our eyes are insufficiently sensitive)

• Magenta predominates below 100km.

• Magenta is a combination of N² and O⁺² emissions near 600nm and N⁺² violet emissions.
Precipitating particles equatorward of 68.5° produce the diffuse aurora.

- Aureol-3 (French for aurora) observations of electrons and ions precipitating into the nightside ionosphere.
  - Middle panel shows average energy
  - Bottom panel shows the energy flux to the ionosphere.
- Ion signature around 2124 UT is a velocity dispersed ion structure thought to be the signature of the PSBL.
- Red electron fluxes equatorward are “inverted V” events associated with discrete aurora.
- Total hemispheric electron precipitation is $9.4 \times 10^{25} \text{ s}^{-1}\text{sr}^{-1}$ to $6.4 \times 10^{26} \text{ s}^{-1}\text{sr}^{-1}$.
- Total hemispheric ion precipitation is $2.3 \times 10^{23} \text{ s}^{-1}\text{sr}^{-1}$ - $9.4 \times 10^{24} \text{ s}^{-1}\text{sr}^{-1}$
• Particles in the magnetotail experience three types of motion depending on

\[ \kappa^2 = \frac{qLB_n^2}{muB_{lobe}} = \left( \frac{R_{C_{\text{min}}}}{\rho_{G_{\text{max}}}} \right) \]

the ratio of the minimum field line radius of curvature \((R_{C_{\text{min}}})\) to the maximum particle gyroradius \((\rho_{G_{\text{max}}})\). In this equation q is the charge, u the particle velocity, \(B_{lobe}\) the magnetic field strength in the lobes and L is a scale length for changes in the tangential component as it reverses direction, and \(B_n\) is the normal component of the field.

- \(\kappa^2 >> 1\) gives guiding center motion
- \(\kappa^2 << 1\) gives Speiser motion
- Pitch angle scattering does not occur for either of these.

• Particles with intermediate values of \(\kappa^2\) undergo chaotic motion and can be scattered into the loss cone.

- The loss cone is defined by pitch angles \((\cos(\alpha) = \frac{\vec{u} \cdot \vec{B}}{|uB|})\) for which the particles mirror in the atmosphere.
- Values of \(\kappa^2\) between 0.1 and 8 have been found to give precipitation.
- The VDIS are thought to result from this.
• Wave - particle interactions cause particles to move in velocity space in response to the electric field force of the wave field.

• Magnetospheric waves having an electric field component parallel to the ambient magnetic field (e.g. Langmuir waves, ion acoustic waves, electrostatic cyclotron waves, lower hybrid waves) can resonantly scatter particles in the direction parallel to \( \vec{B} \) and thus contribute to net particle flux to the ionosphere.

• Waves also have an electric field perpendicular to the magnetic field. Resonance with the perpendicular electric field involves the gyromotion of the particle and occurs when the wave frequency (\( \omega \)) in the frame of reference of the particle’s motion along \( \vec{B} \) equals a harmonic (\( n \)) of the particles gyrofrequency (\( \Omega \)). If \( k_{\parallel} \) is the parallel wave number then the condition for resonance is
\[
\omega - k_{\parallel} u_{\parallel} + n\Omega = 0
\]

• Loss of magnetospheric particles by pitch-angle scattering maximizes if the scatter is strong enough to fill the loss cone in less than one particle bounce period. This is called strong pitch angle scattering.
• Magnetic field-aligned electric fields accelerate electrons toward the atmosphere in regions of upward (away from the Earth) field aligned currents.

• This process usually occurs at altitudes of 5000-10000km and significantly increases the flux of electrons in the loss cone and their energy.

• The parallel potential difference is typically 1 -10kV.

• The distributions of electrons created by the parallel electric field can be unstable to wave particle instabilities.

• Parallel field aligned electric fields are thought to be responsible for discrete aurora.

• The field aligned electric field – right. The distribution functions of precipitating electrons – left.
• Earthward convection in the plasma sheet can move particles closer to the loss cone at distances where gradient and curvature drifts carry particles across electric potentials.
  – As particles convect toward Earth their pitch angles actually increase!
  – However the loss cone gets larger too and some particles are lost.
• Convection is not an important loss mechanism.
• There are four forms of aurora.
  – Quiet homogeneous arcs stretching in an east-west direction across the sky.
  – Auroral rays.
  – Diffuse auroral clouds.
  – Spirals and curls.
• The diffuse auroral oval is associated with the evening region with greatest proton energy flux and maps just inside of the region of stable trapping.
• Auroral forms – courtesy Jan Curtis
• The instantaneous distribution of maximum auroral activity versus magnetic time and latitude was found by Feldstein and Starkov to occupy an oval-shaped belt called the auroral oval.

• The ovals (one in each hemisphere) are continuous bands centered near 67° magnetic latitude at midnight and about 77° at noon during quiet periods and periods of moderate activity.

• The position and size of the auroral oval can be understood by considering the effects of reconnection.
  – When the IMF turns southward dayside reconnection adds magnetic flux to the lobes and the polar cap gets larger.
  – When the IMF turns northward the reconnection moves to the polar cusp, flux is removed from the lobes and the auroral oval gets smaller.
• Cusp auroras form in the daytime polar thermosphere where atomic species are abundant.
  – Atomic bands are more important than molecular.

• The dominant dayside cusp aurora is the diffuse band with $I(630\text{nm}) >> I(557.7\text{nm})$.
  – The cusp aurora is called the “midday gap” because discrete auroral forms are frequently absent.

• Cusp aurora are controlled by the IMF direction.
  – For $B_z < 0$ cusp aurora are stronger as magnetosheath particles have direct access.

  – For $B_z > 0$ high latitude reconnection decreases polar cap size and transport to cusp.
• Polar-cap sun-aligned auroras are found “across” the polar cap oriented from midnight to noon.

• Polar-cap auroras occur about 50% of the time when IMF $B_Z > 0$.

• Polar-cap auroras are thought to be associated with four cell convection patterns caused by high latitude reconnection.
  - For IMF $B_Z > 0$ two convection cells form at high latitudes: tailward flow at lower latitudes and sunward at higher latitudes.
  - The sunward convection seems to be associated with the polar arc.

  – Where the fields converge so does the Pederson current. This current closes by moving upward. (Note there is a downward current on the opposite side.)
  – The upward current (downward electrons) causes the aurora.

• Near the flow reversal there are two regions with oppositely directed electric fields.
• Large auroras follow a fixed pattern.
  – The pattern starts with one or more quiet arcs (1-10 kR) elongated in the east-west direction.
  – After some time the aurora starts to move equatorward and brighten.
  – Then the sky explodes and aurora spreads over the entire sky.
  – The aurora moves rapidly with many changes in intensity (100s of kR) and form. Forms move at 10km/s across the sky.
  – The auroral then becomes weak (1-5 kR) and diffuse.
• Typically the “substorm” process repeats in 0.5 - 3 hours.
VIS Earth Camera
23 Sep 1996 (96/267)

03:09:36 UT
03:12:19 UT
03:15:01 UT
03:17:43 UT
03:20:25 UT
03:23:08 UT
03:25:50 UT
03:28:32 UT

Visible Imaging System/POLAR
The University of Iowa
• Currents flow between the dawn and dusk regions of the magnetosphere across the tail current sheet separating the tail lobes.

• Most go across the magnetosphere but some are diverted along the field lines into and across the auroral ionosphere.
  - These currents are carried by electrons which are more mobile than the ions.
  - High latitude currents enter the ionosphere at dawn and exit at dusk.
  - The earthward currents are carried by upgoing thermal electrons.

• The currents away from the Earth are carried by precipitating electrons. These form the dusk side aurora.

• At lower latitudes the outward currents are on the dawn side and form aurora.