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Auroral Physics

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WDC for Aurora

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Wintering at Syowa Station in
the Antarctic in 1989 and 2003
to do auroral observations

Outline

- ✧ Brief history of auroral study
- ✧ Auroral basics
- ✧ Auroral substorm
- ✧ Some other issues

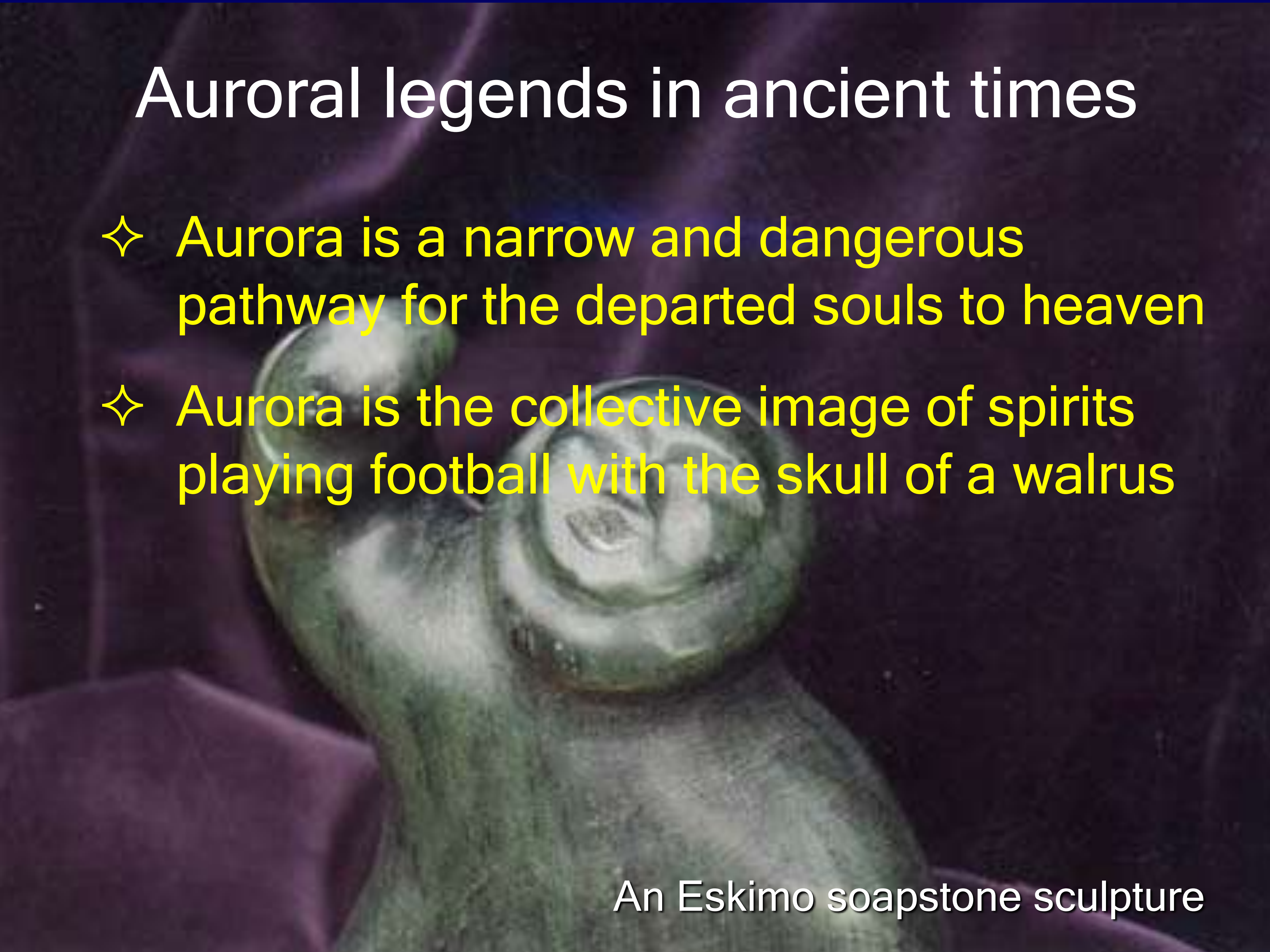
“Aurora”

Goddess of Dawn
in Roman mythology
(equivalent of “Eos”
in Greek mythology)

Who named ?
Galileo Galilei
(Italy, 1619)

Auroral legends in ancient times

- Aurora is a narrow and dangerous pathway for the departed souls to heaven
- Aurora is the collective image of spirits playing football with the skull of a walrus



An Eskimo soapstone sculpture

Aurora in the Medieval Period

Candles in the heaven

Aurora in the Medieval Period

Fire from a crack of heaven

Aurora in the Medieval Period

A bad omen of unhappiness or war

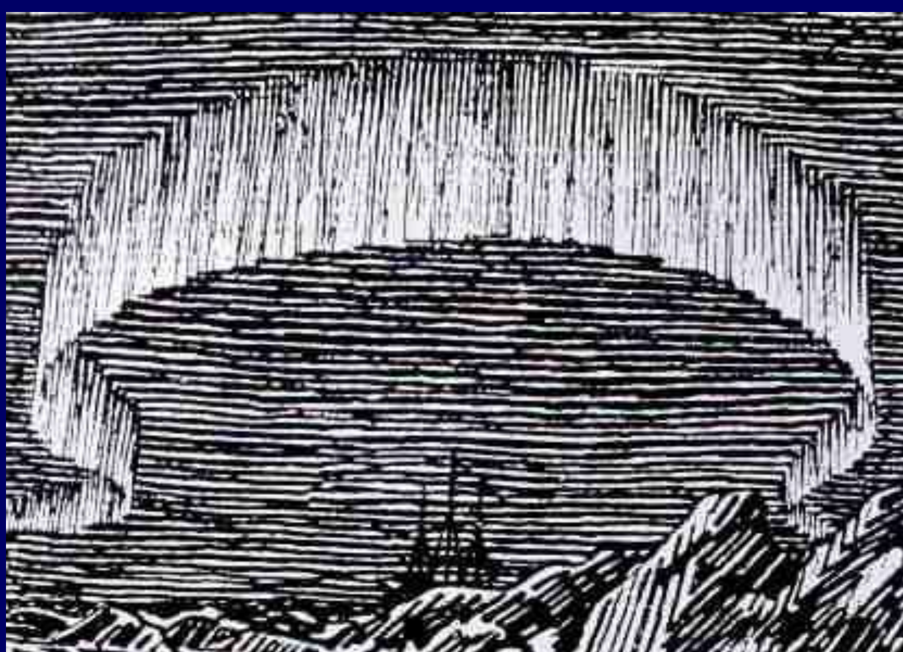
Aurora in the Medieval Period

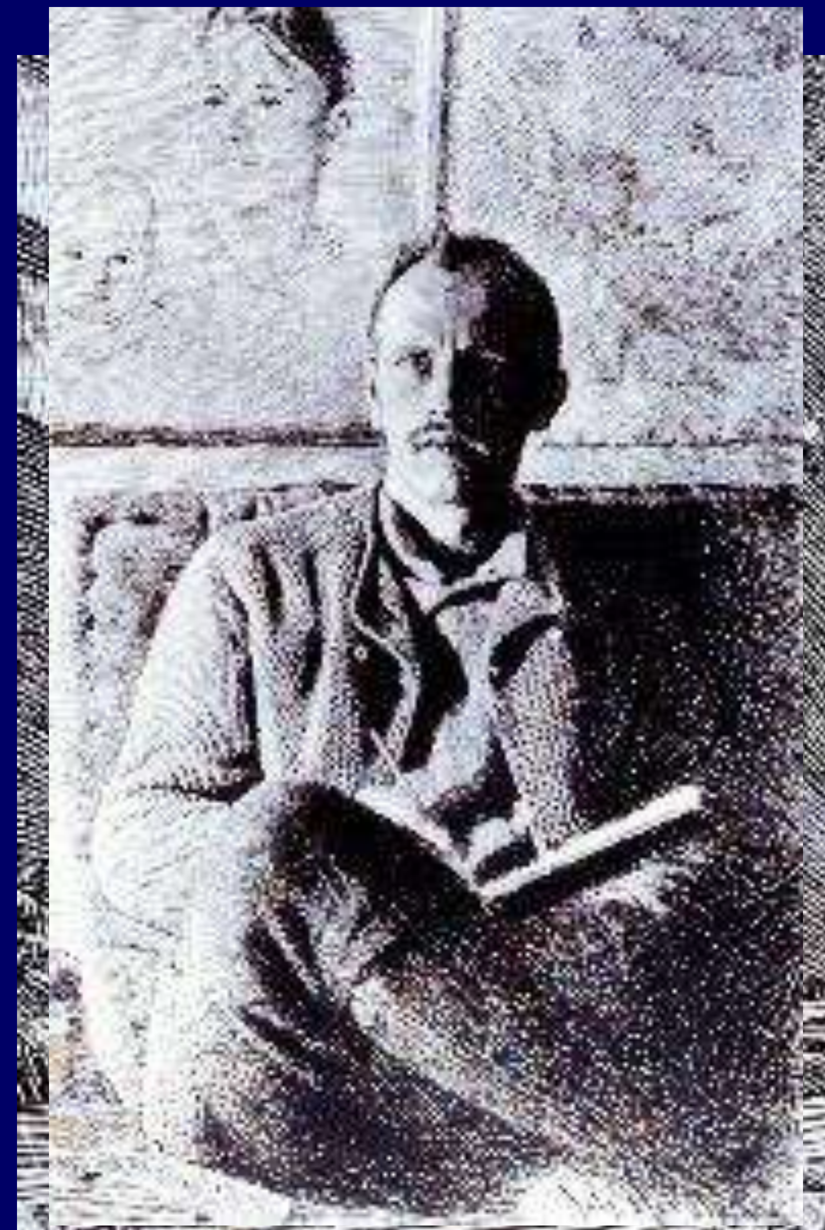
Sparks from a battle in the sky

Aurora recorded by the polar explorers

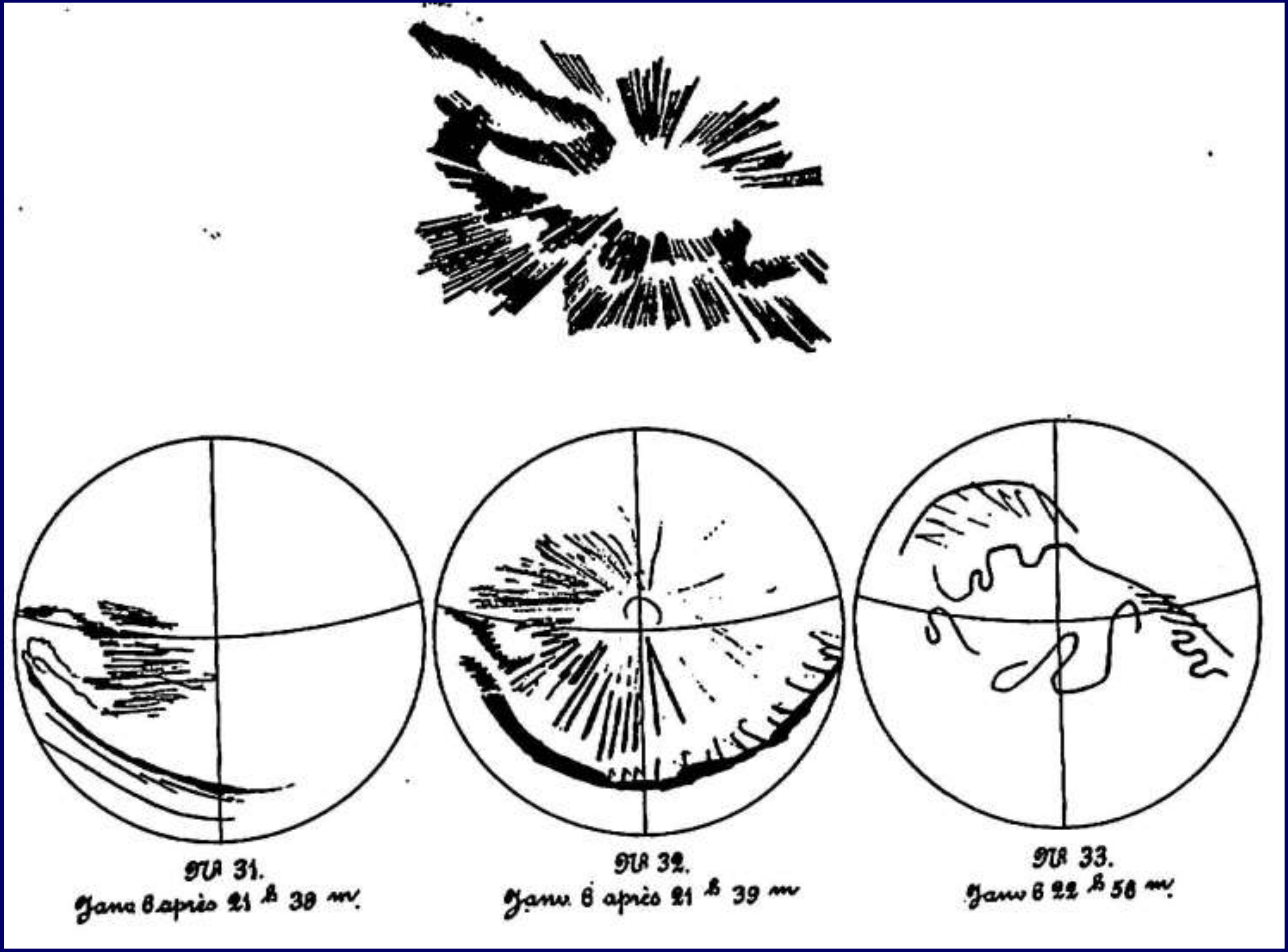
Fridtjof Nansen (Norway)

Expedition to north pole
with the ship Fram
(1893-1896)



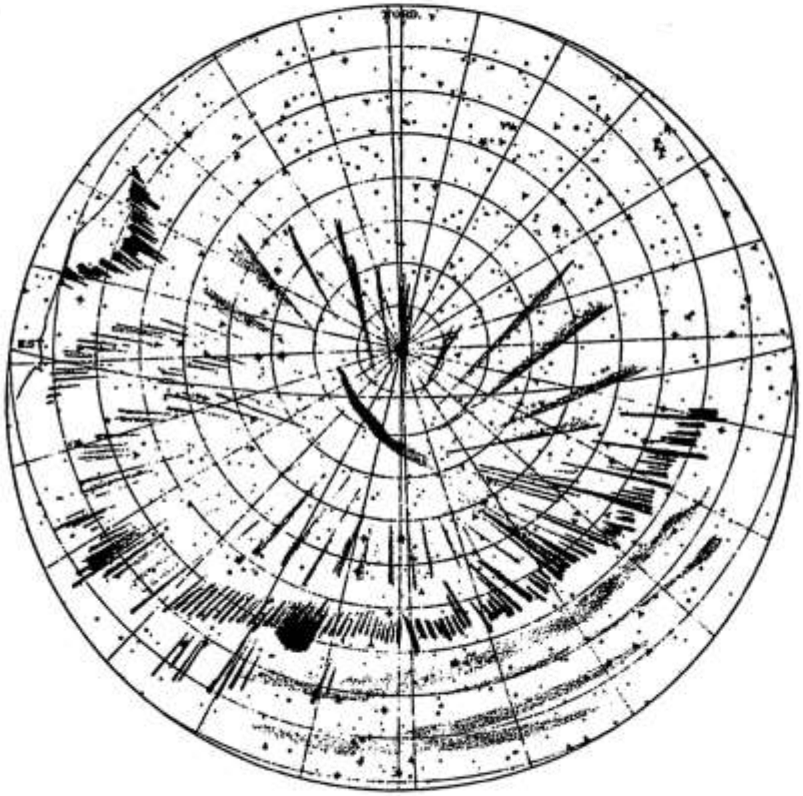


Recorded by eye & hand



Auroral sketches in 1886

Recorded by eye & hand



Projection polaire de la sphère céleste représentant l'aurore boréale du 6 janvier à 21 h 45 m – 21 h 50 m.

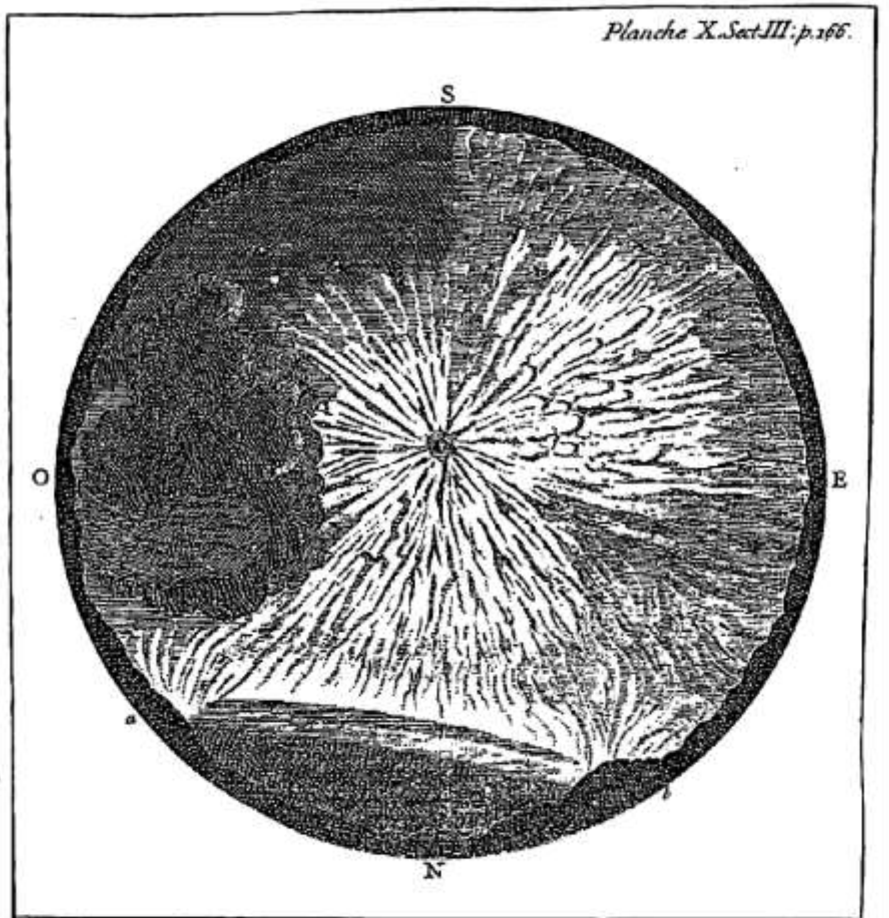


Fig. XVII. Aurore Boréale du 19.me Octobre 1726. telle qu'elle parut dans tout l'Hemisphere Superieur du Ciel, vers les 8. heures du Soir, à Breuillepont, Diocese d'Evreux, 15 ou 16 Lieues à l'Occident de Paris.

in 1886

in 1926

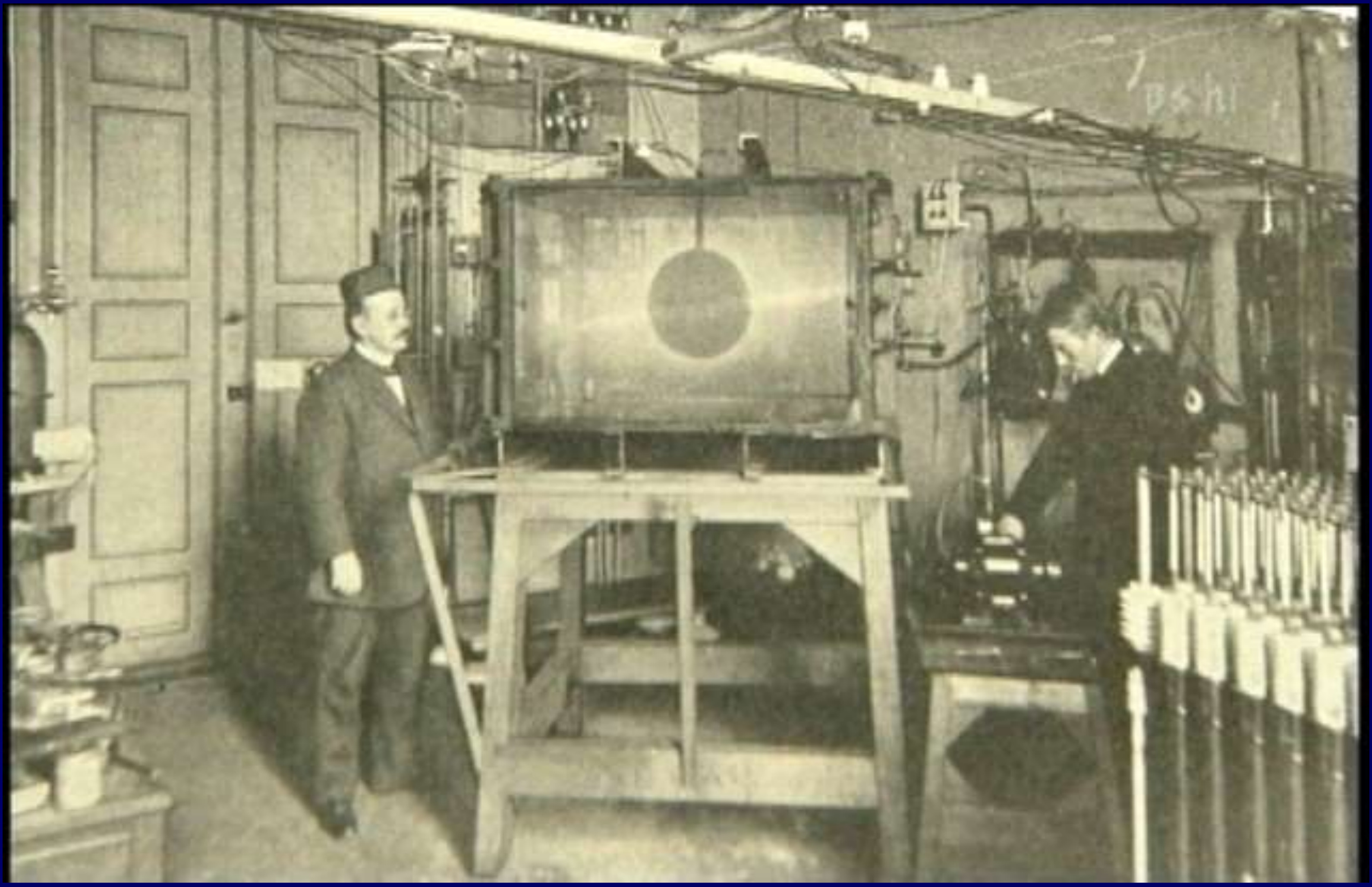
Observation by eye

Fig. 1.5. K. Birkeland (standing) and C. Störmen (sitting), photographed near Tromsø in 1910.

Birkeland and Störmer in 1910

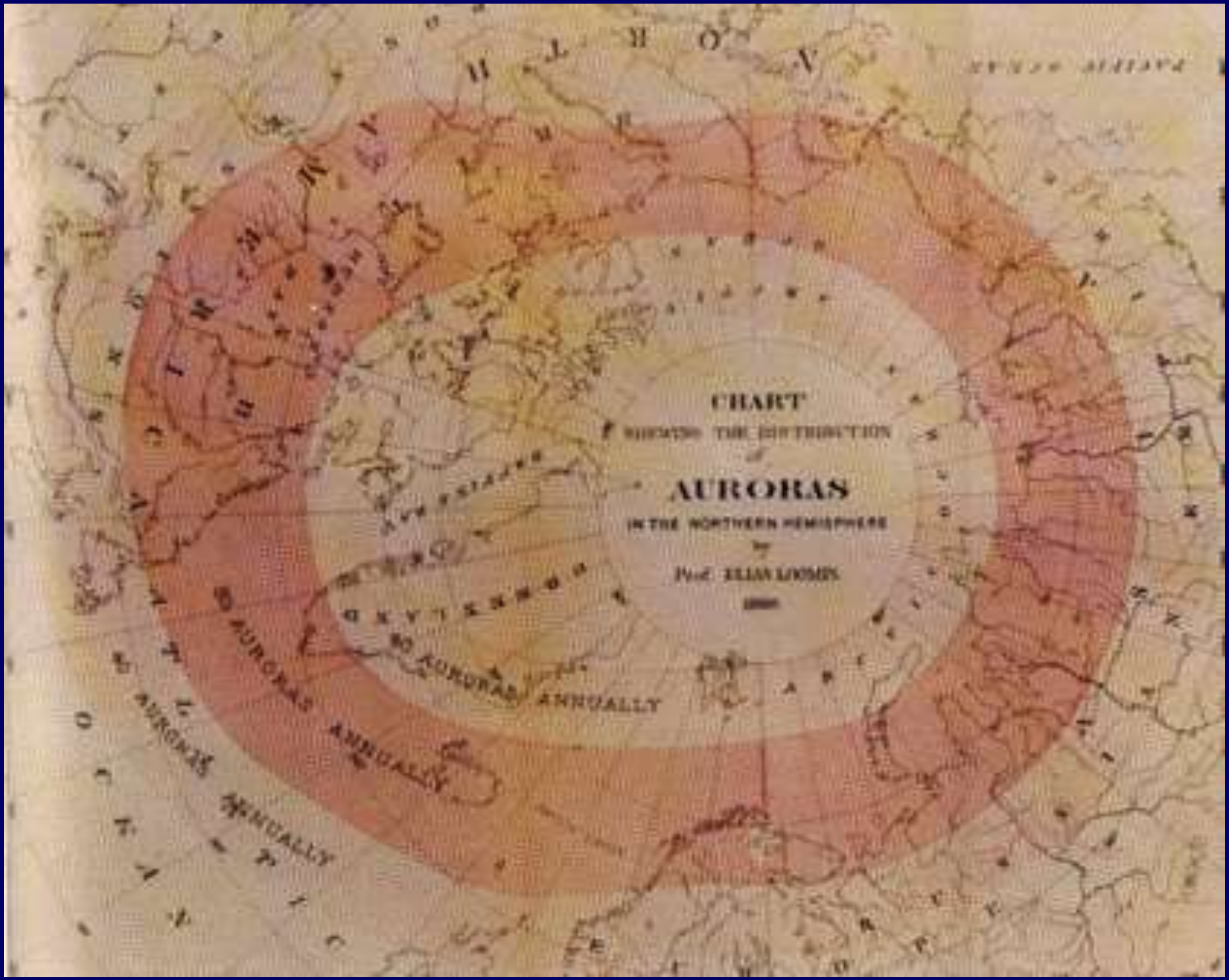
Laboratory Experiment for artificial aurora

Kristian Birkeland (Norway) (1867-1917)



Birkeland and his terrella (meaning "little earth")

Auroral frequency distribution



Elias Loomis (1860)

Auroral frequency distribution

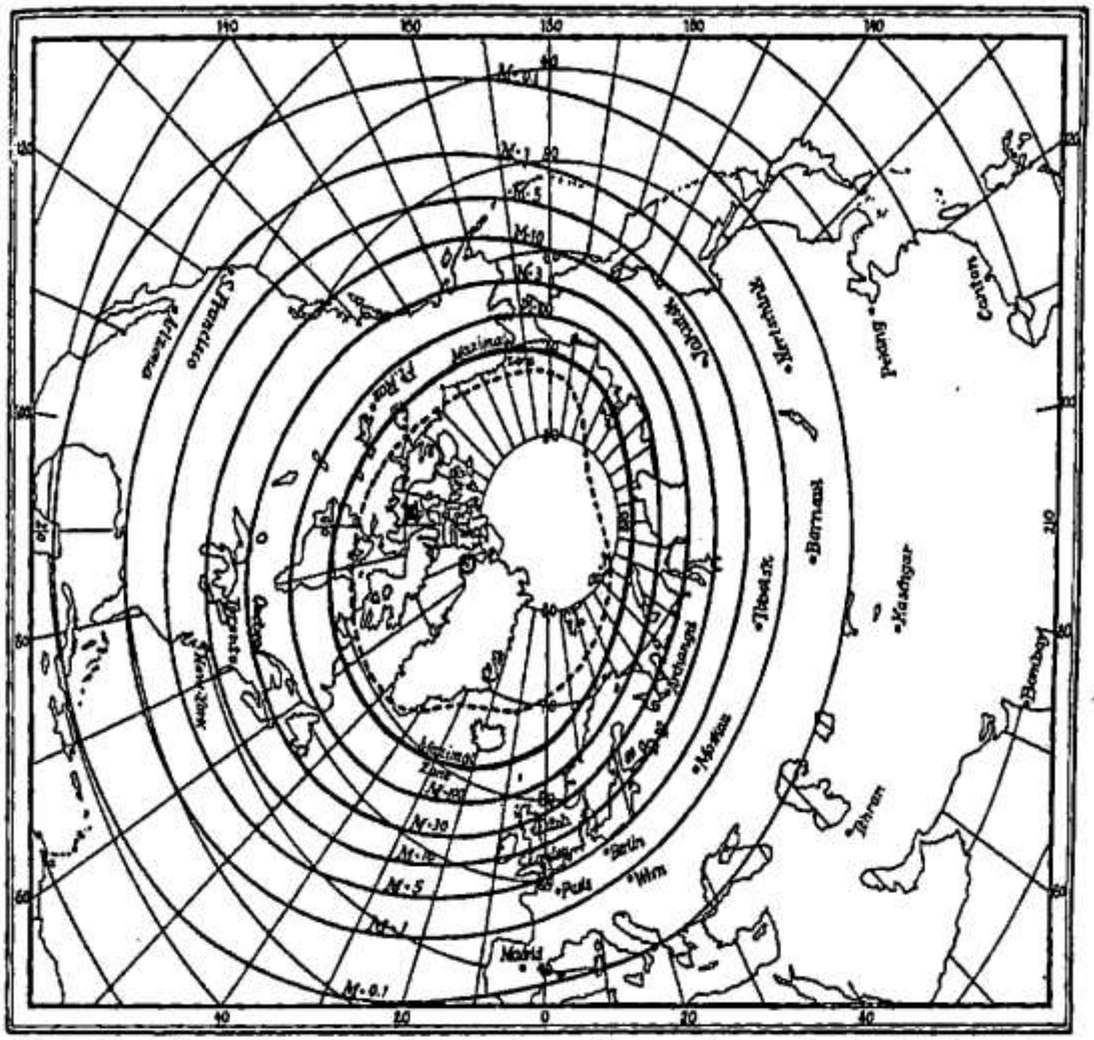
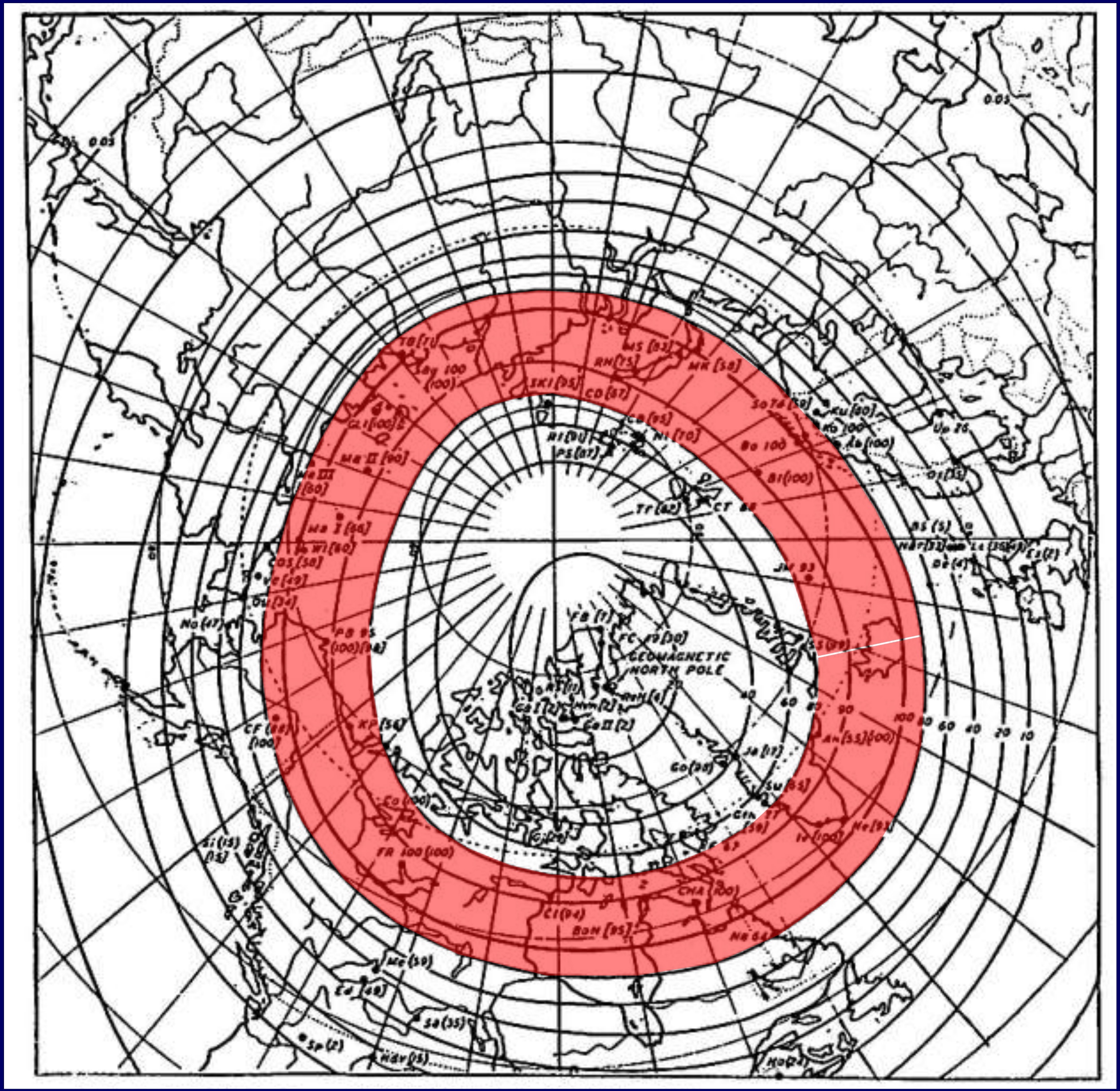


FIG. 7. The distribution of isochasms, or lines of equal auroral frequency, in the northern hemisphere, according to Fritz

Fig. 1.2. Fritz's isochasms in the northern hemisphere.

Hermann Fritz
(1881)

Auroral occurrence distribution

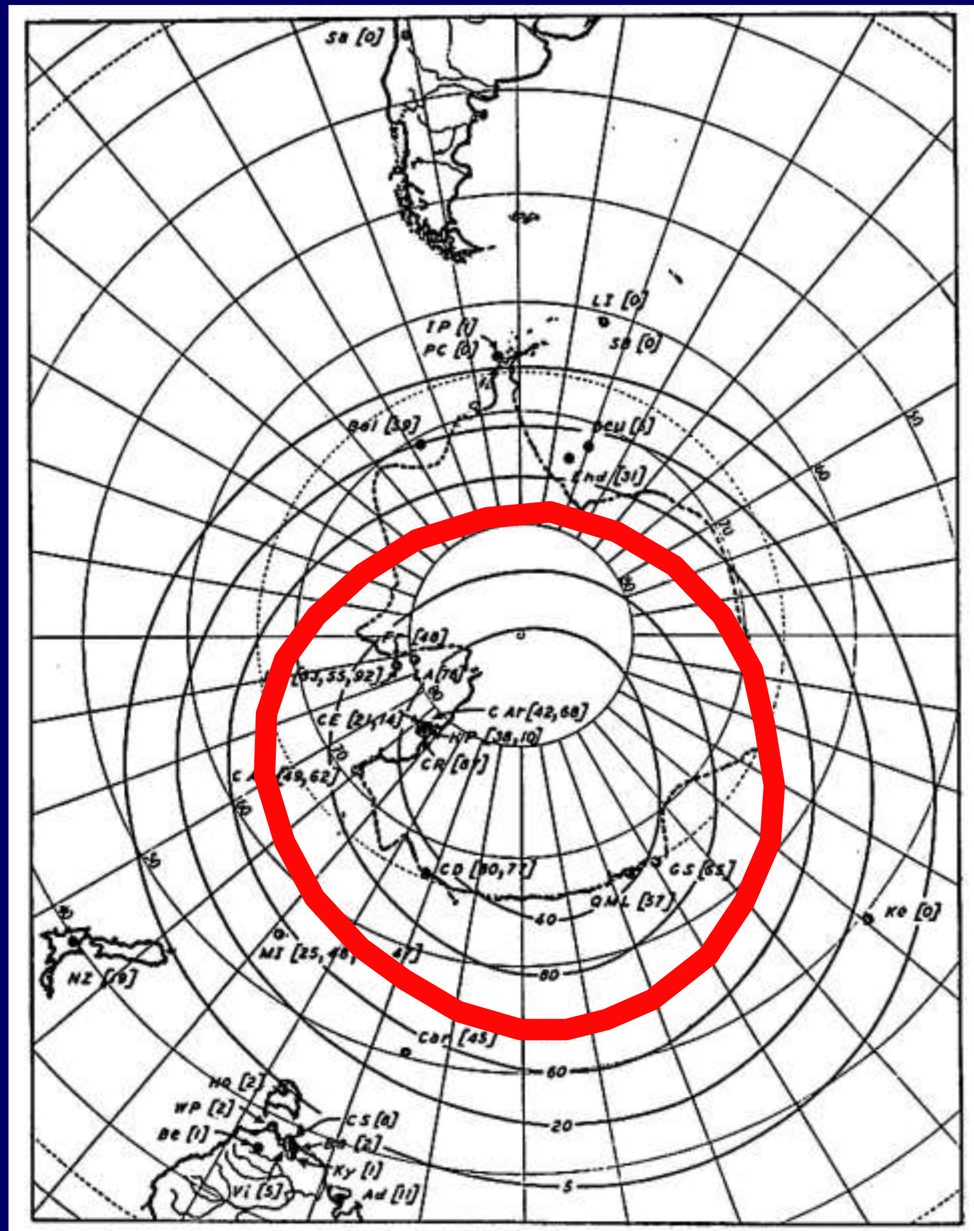


Northern Hemisphere

days/year

Vestine (1944)

Auroral occurrence distribution

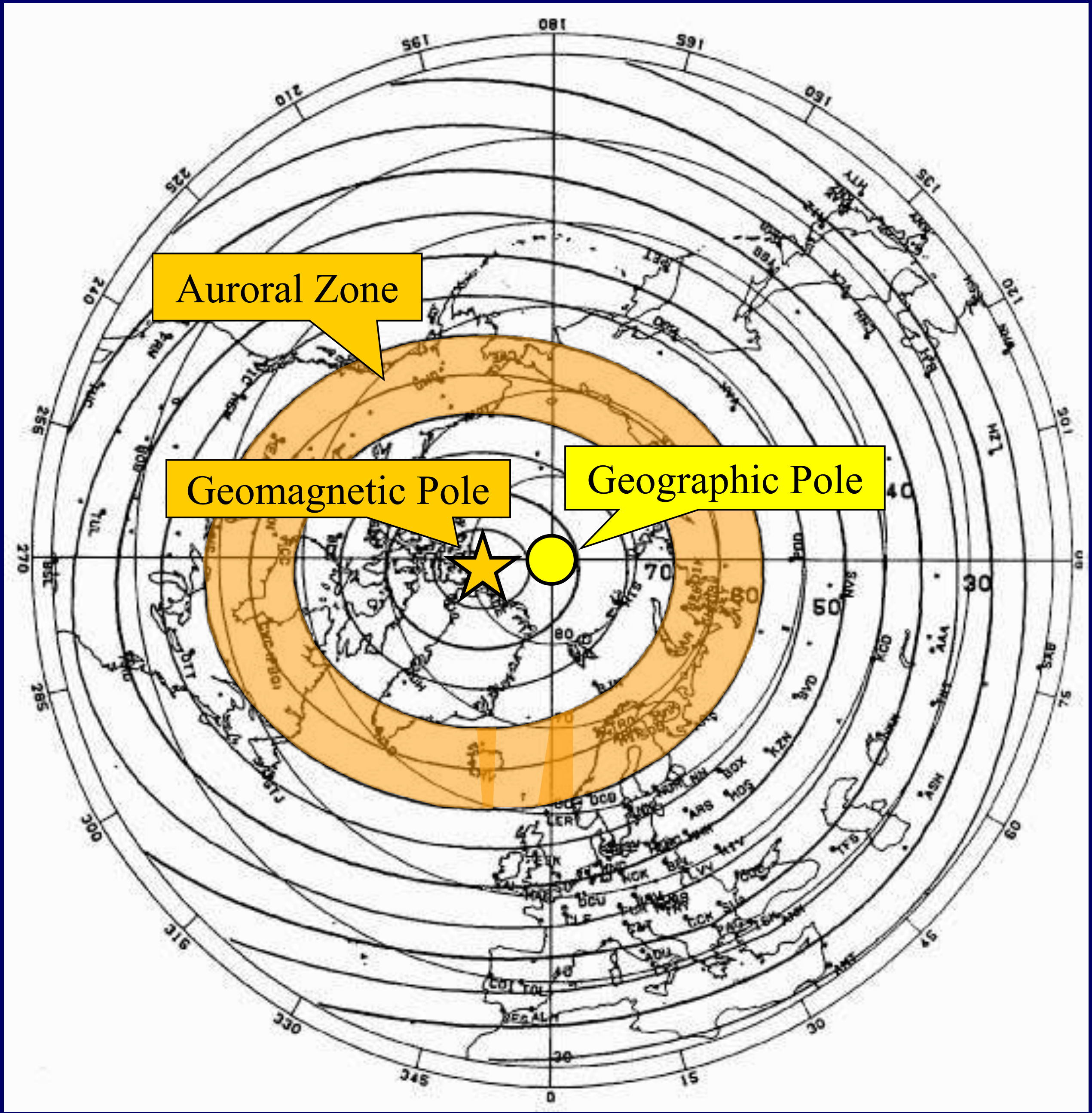


Southern Hemisphere

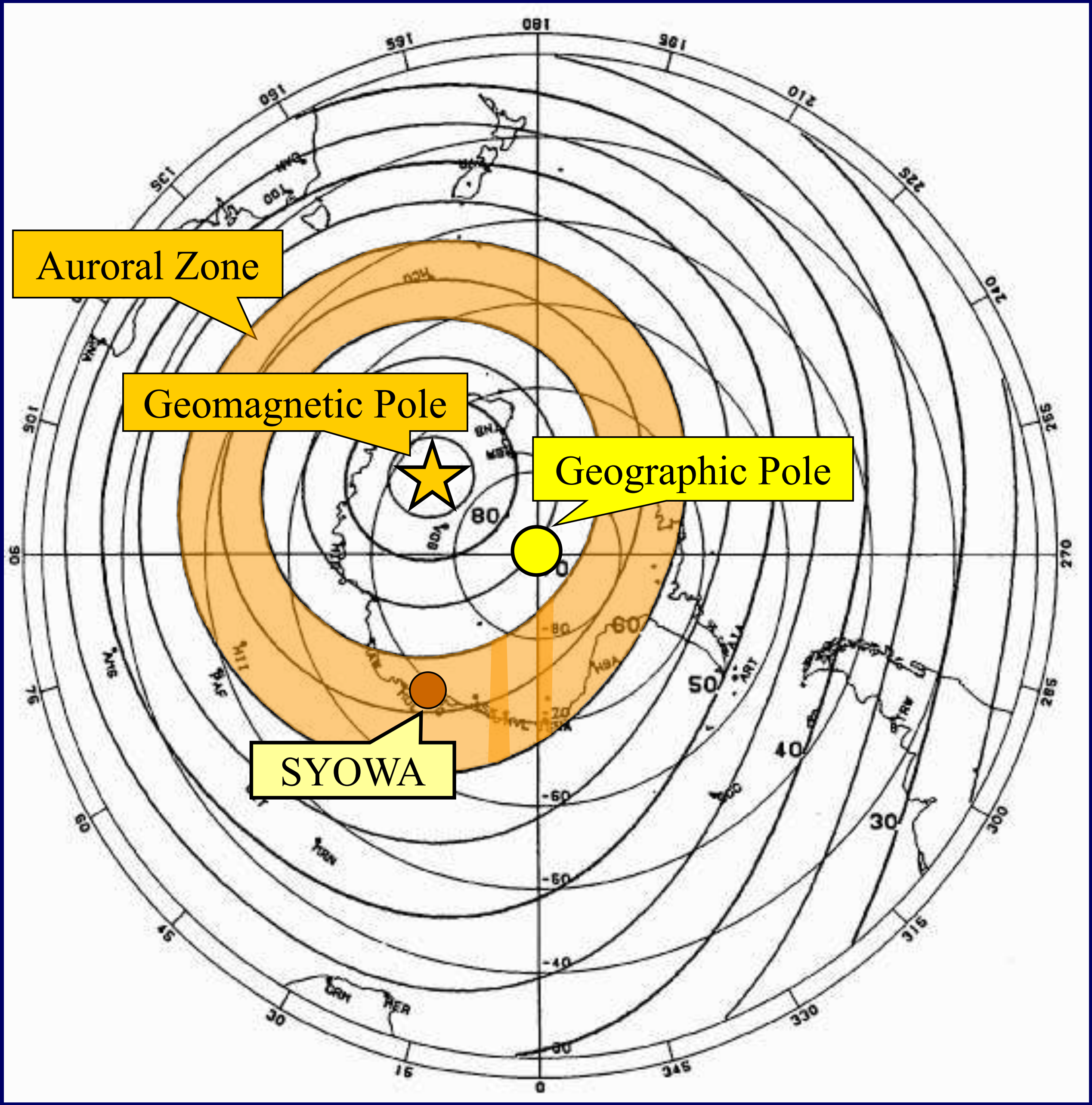
days/year

Vestine and Synder (1945)

Auroral Zone



Auroral Zone



Observation with optical instruments

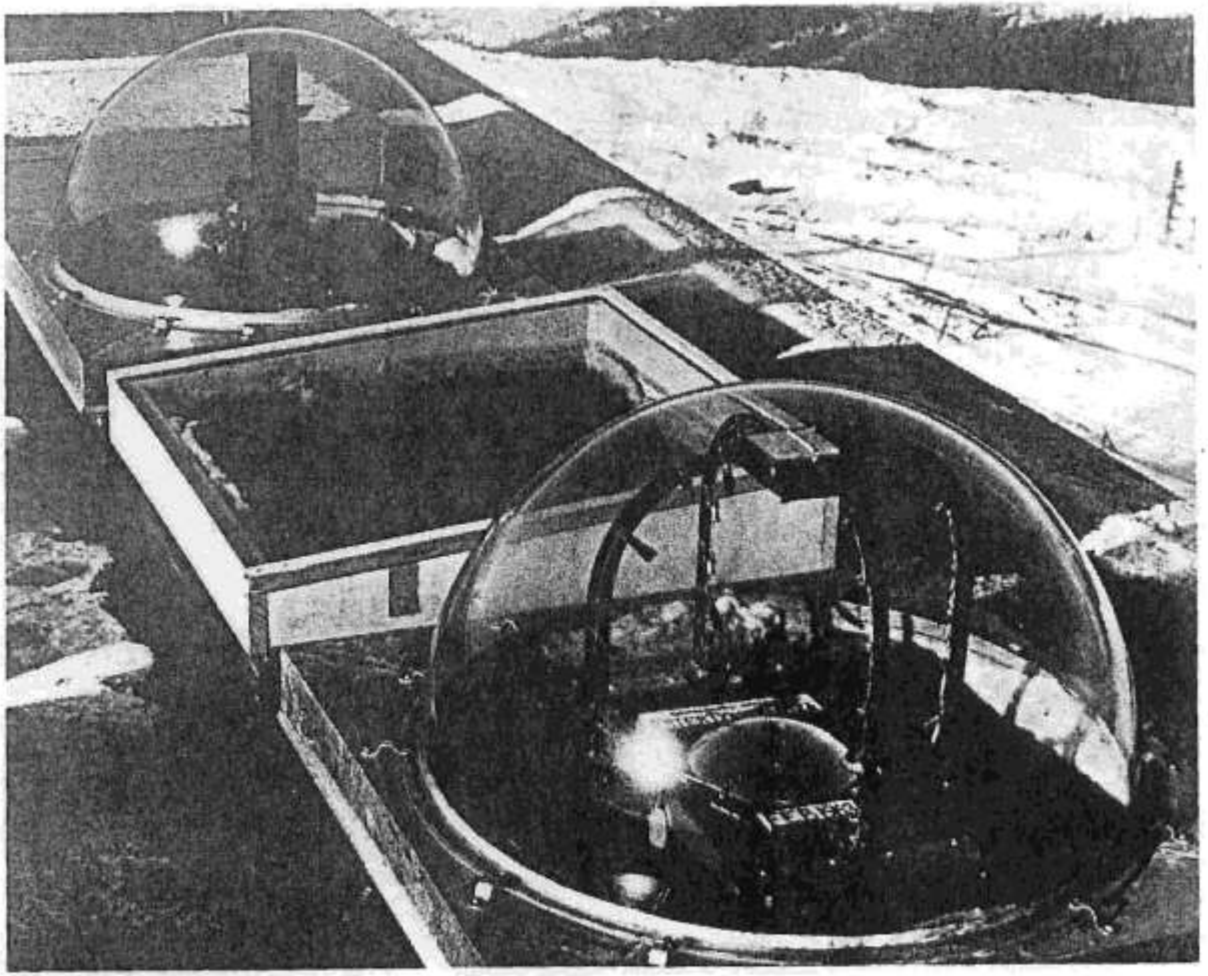


Fig. 1.8. A photograph of the Alaskan 16 mm all-sky camera installed at Ester Dome (College), Alaska. A photometer is also seen in the background.

All-sky camera (front) and photometer (back)

IGY (International Geophysical Year) 1957-1958

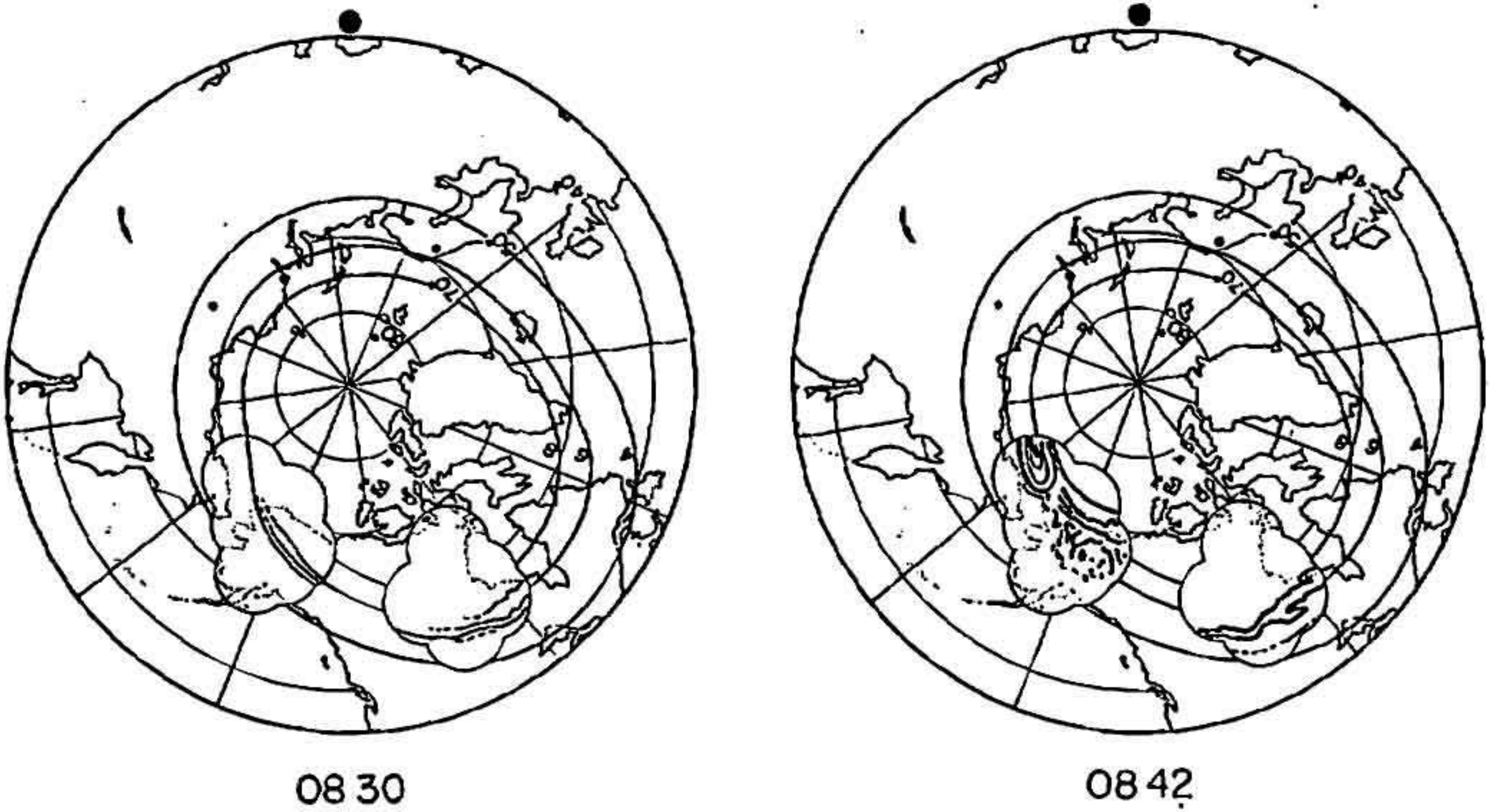


Fig. 1.10. The distribution of the auroras at 0830 and 0842 UT on February 13, 1958. The field of view of each all-sky camera station is indicated by a circle of radius 500 km.

100 All-sky cameras in the world

Auroral Oval

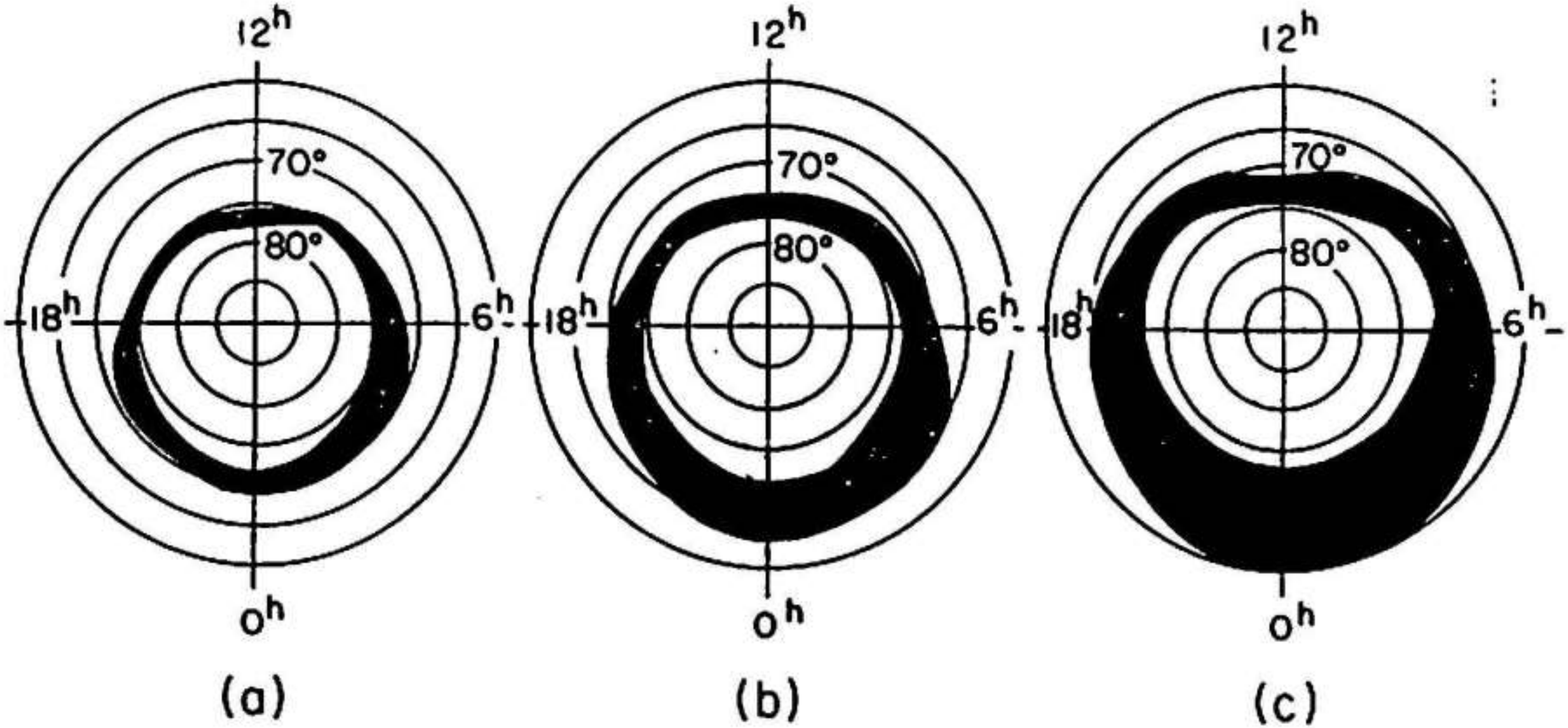
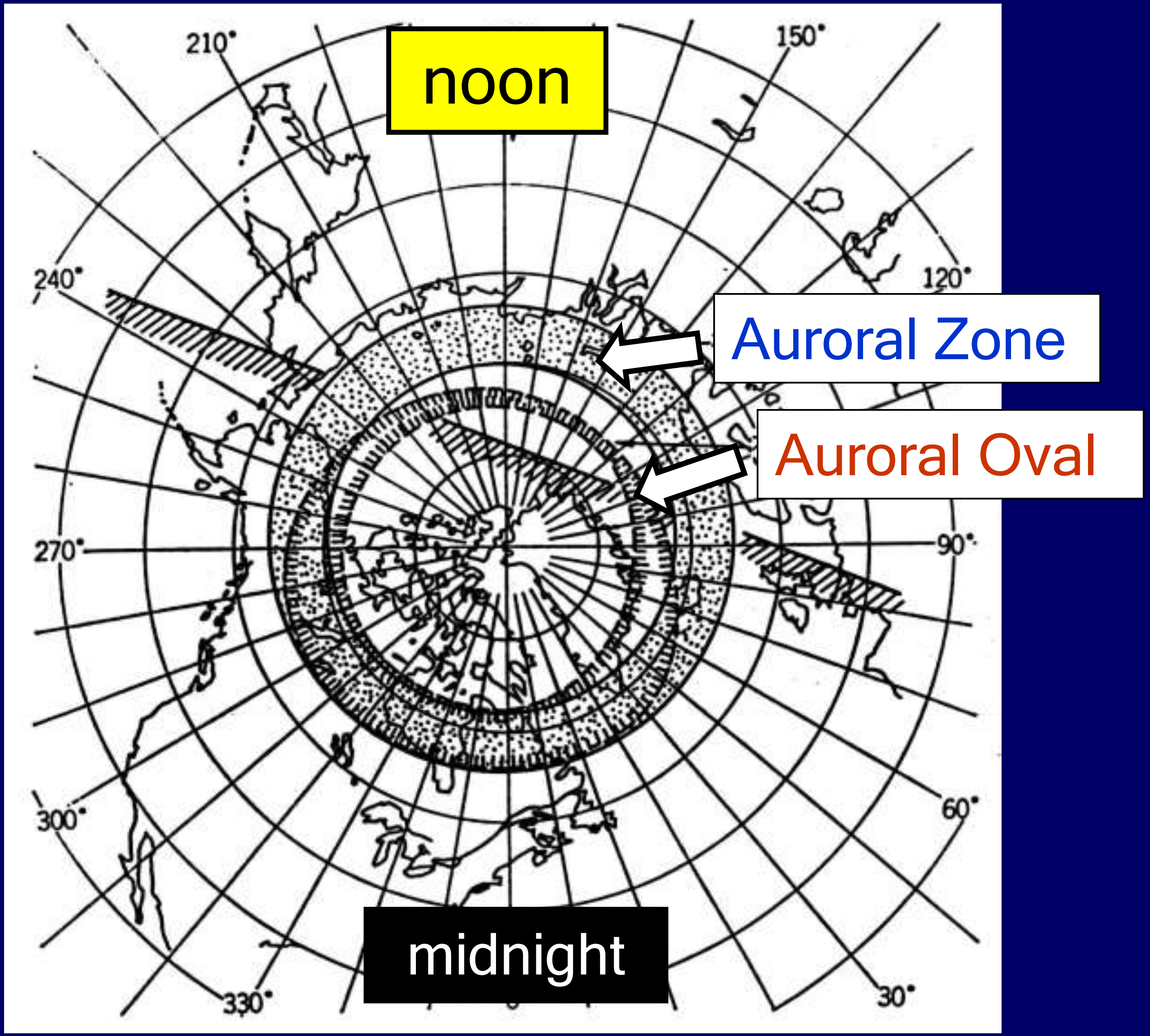


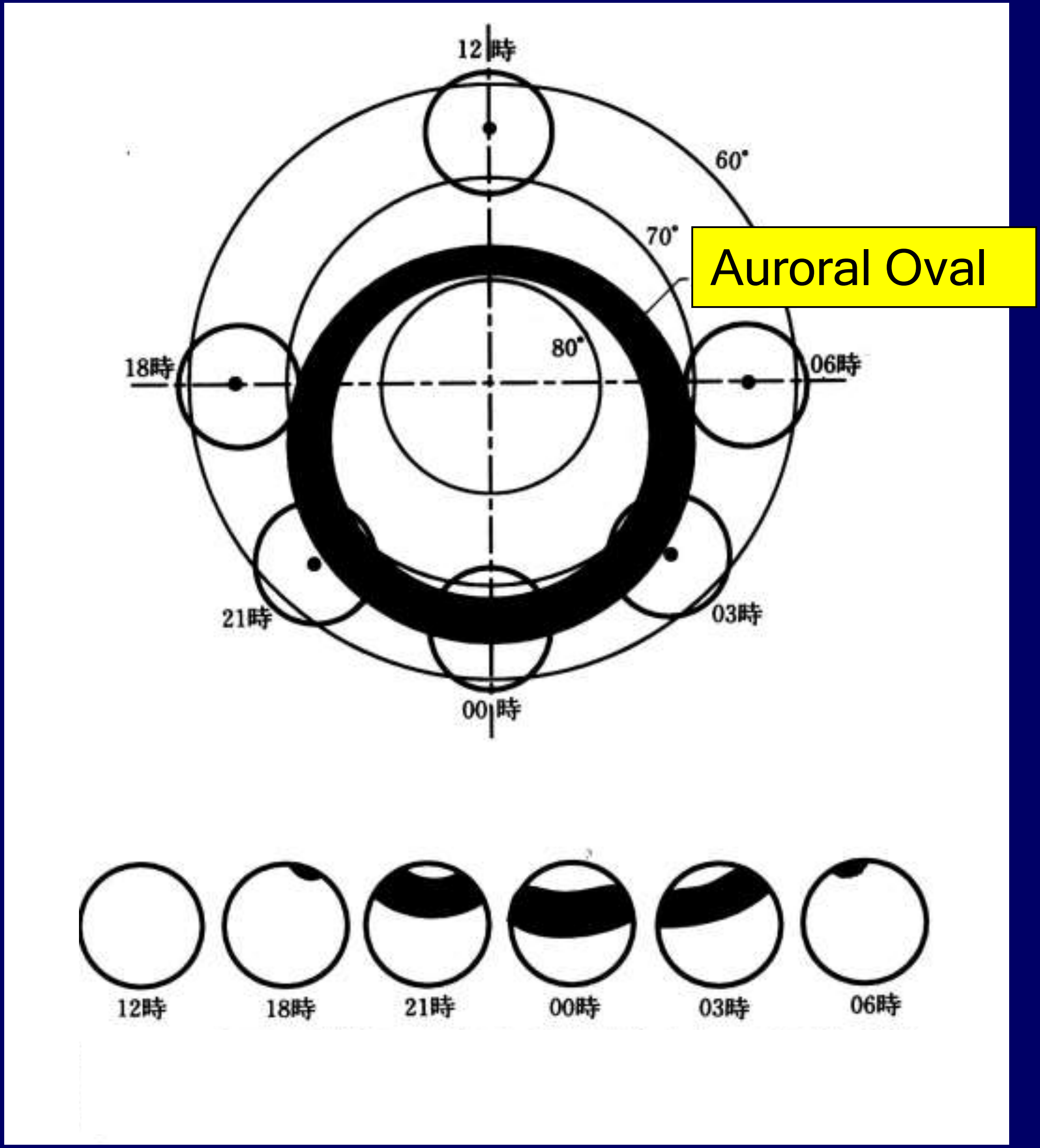
Fig. 3.2. Auroral oval for various levels of magnetic disturbance index Q after Starkov and Feldstein (1968). (a), (b), and (c) are for Q equal to 0, 3, and 7 respectively. The mean oval is similar to (b).

Feldstein and Starkov (1967)

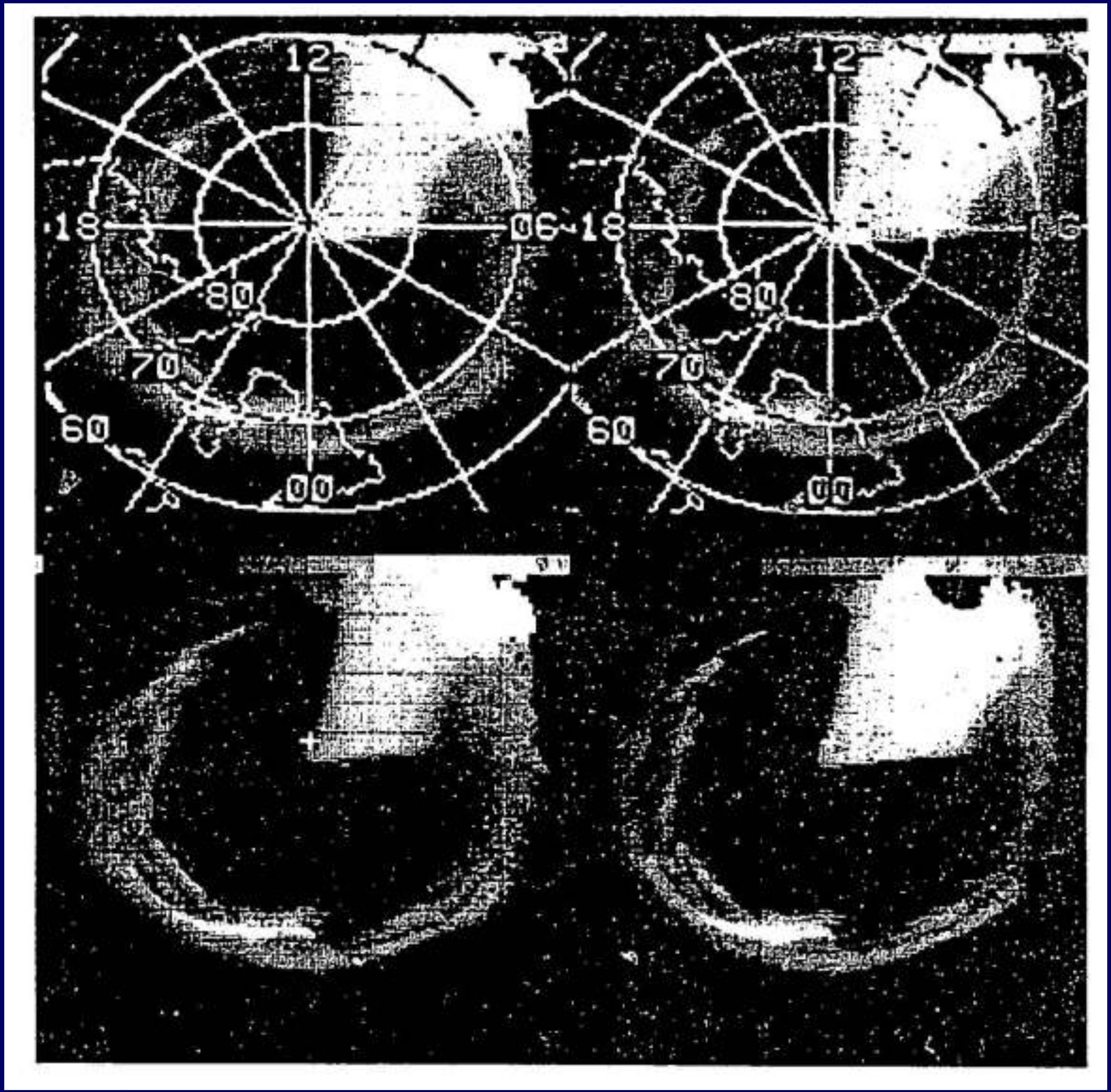
Auroral Zone and Auroral Oval



Auroral Oval and ground FOV (Field of View)



Begin of Satellite age



ISIS-2
(1971)

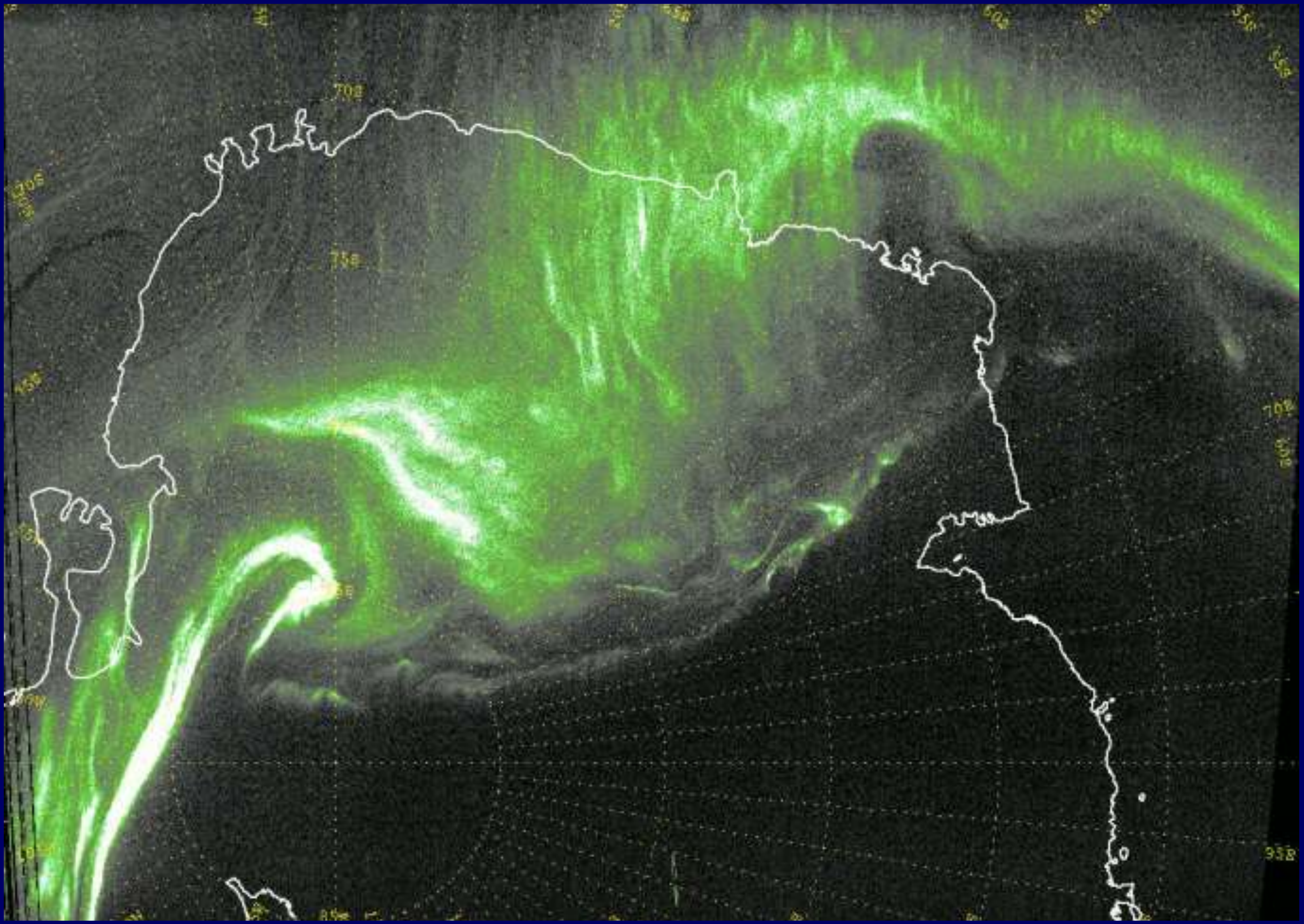
391.4, 557.7 nm

Spin
Scanning
Photometer

altitude
1400 km

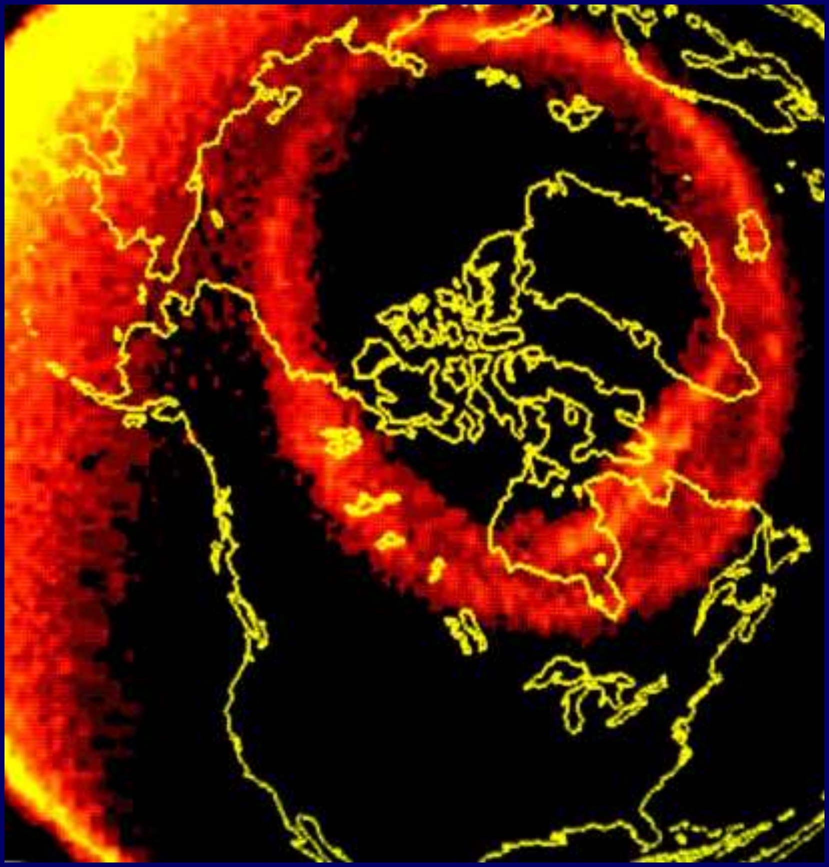
Δt =114 min

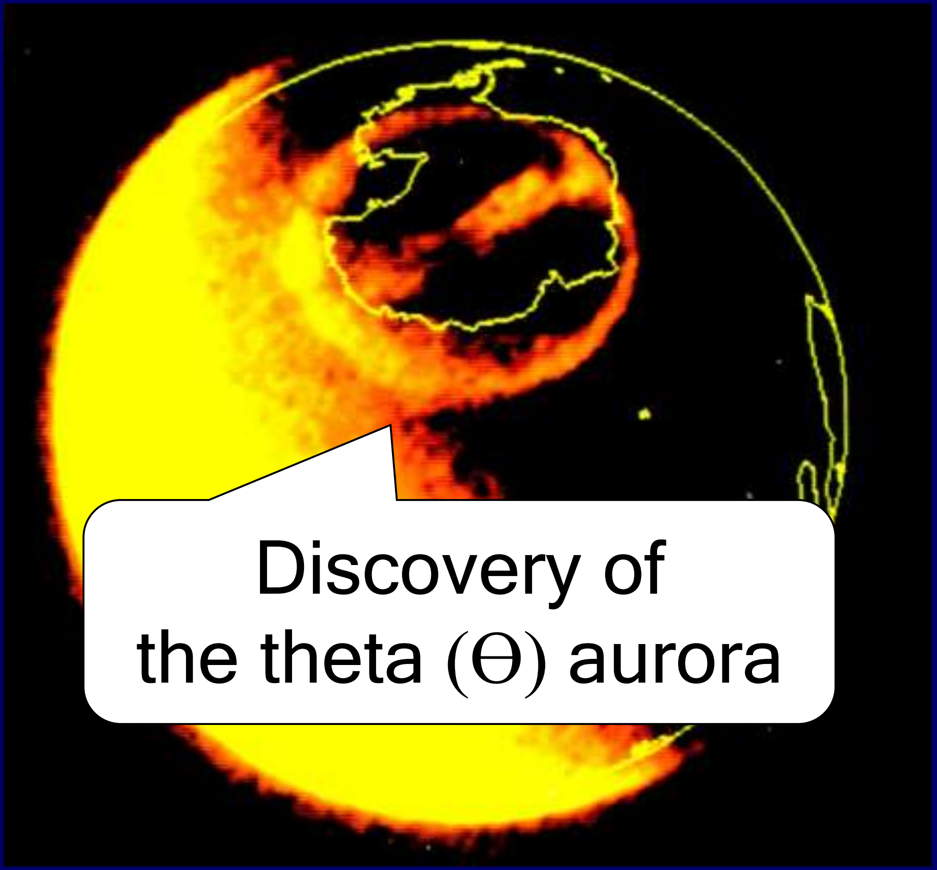
DMSP (Defense Meteorological Satellite Program) Satellite (1973 ~ present)



Visible (400～1,100 nm), Scanning Mirror
altitude: 830 km, Δt =101 min

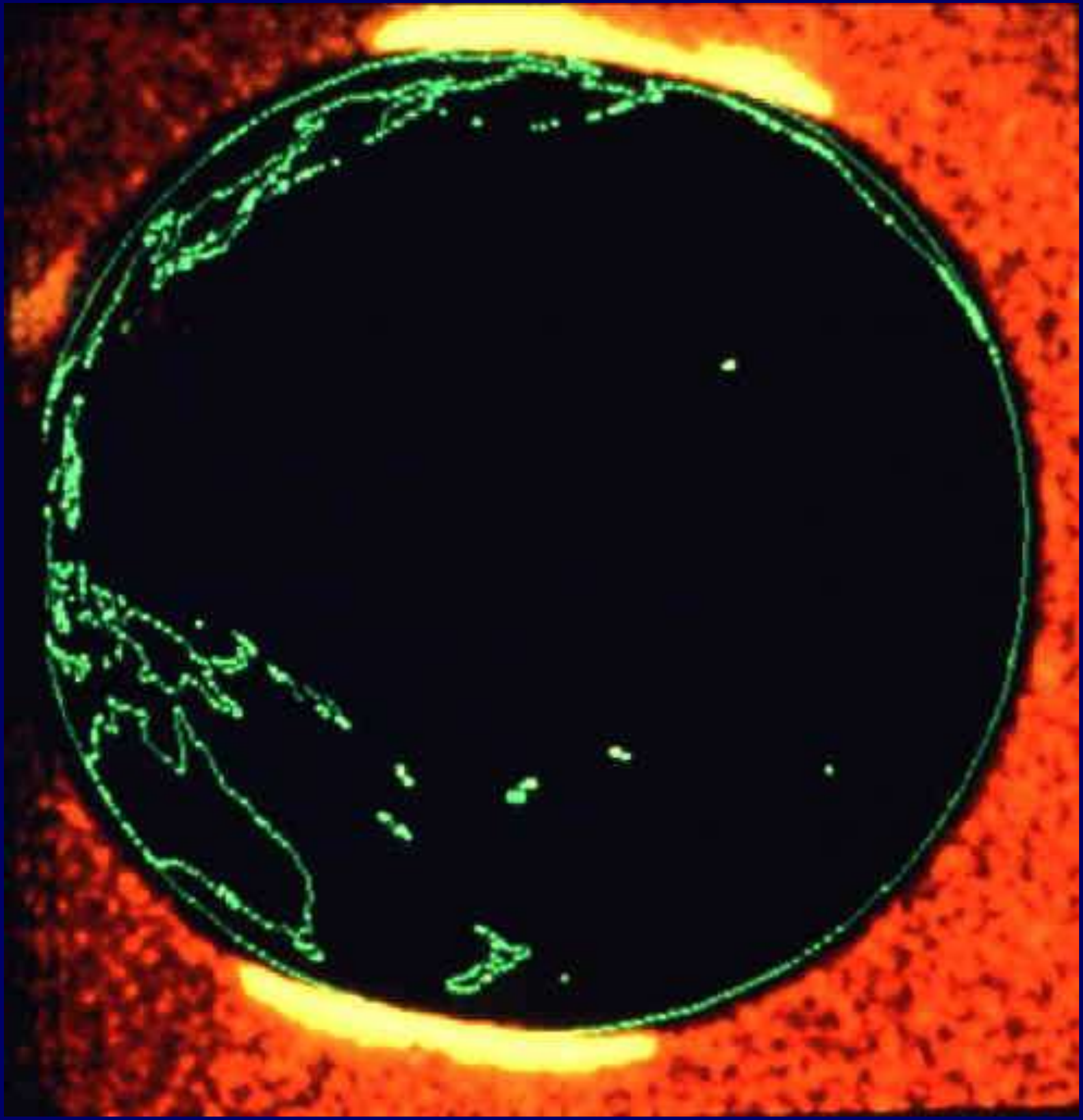
DE-1 (Dynamics Explorer) (1981)



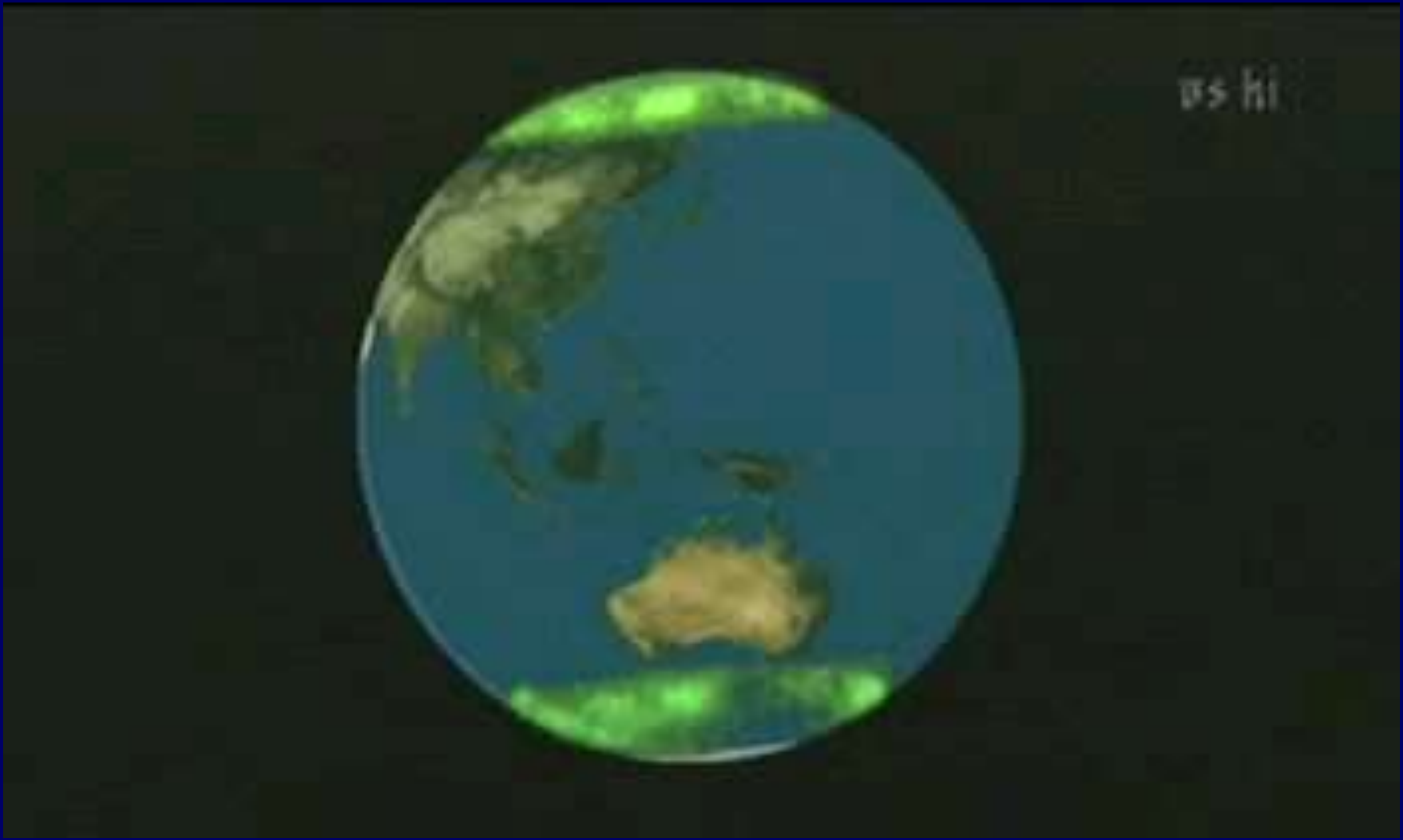


VUV (120～156 nm), Rotating Mirror
altitude: 3.63 Re x 570 km, Δt =12 min

DE-1 (Dynamics Explorer)

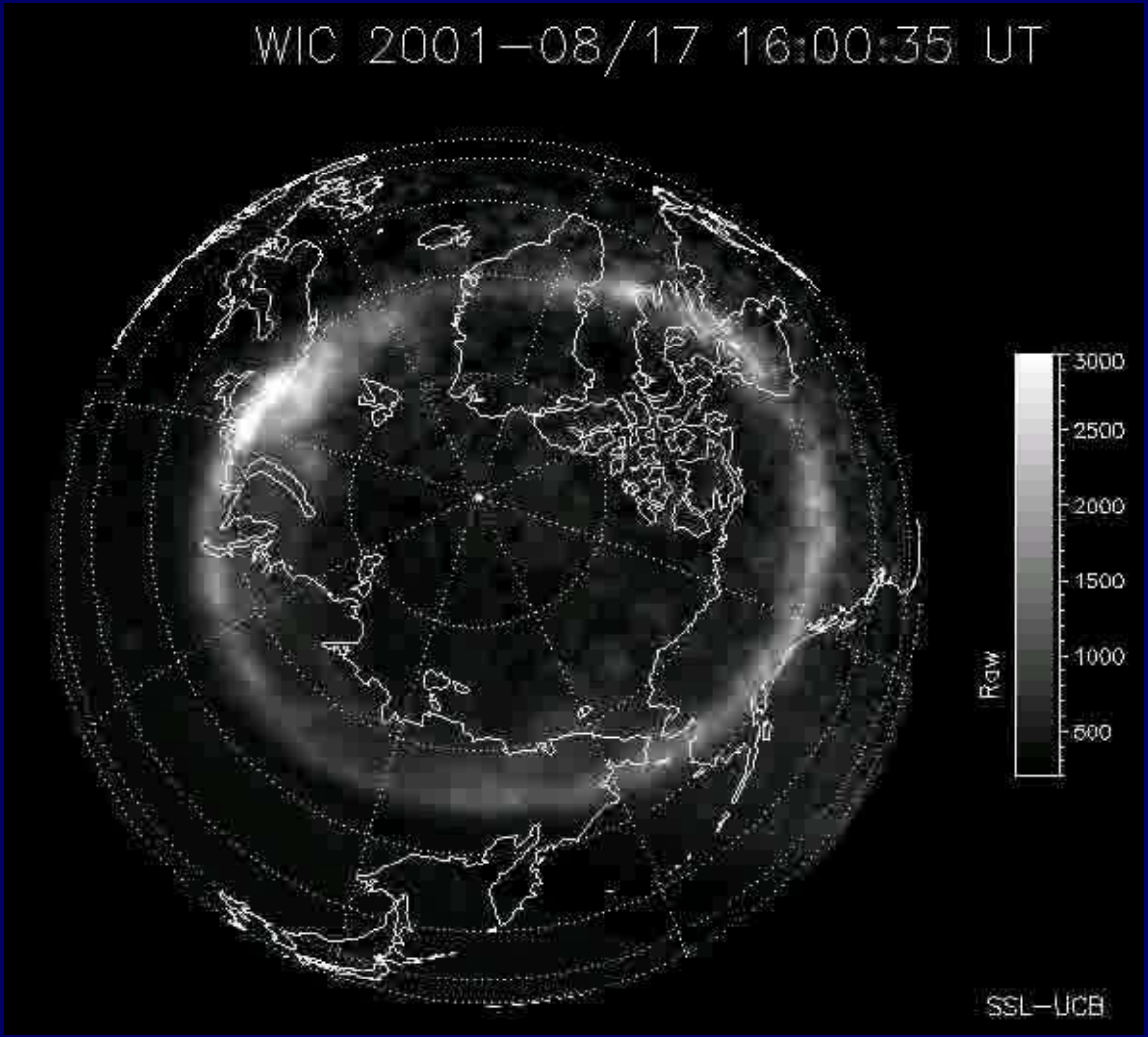


Polar (1996)



Earth camera (123～149 nm), CCD
altitude: 7.9 Re x 185 km, Δt =12 sec

IMAGE (2000)

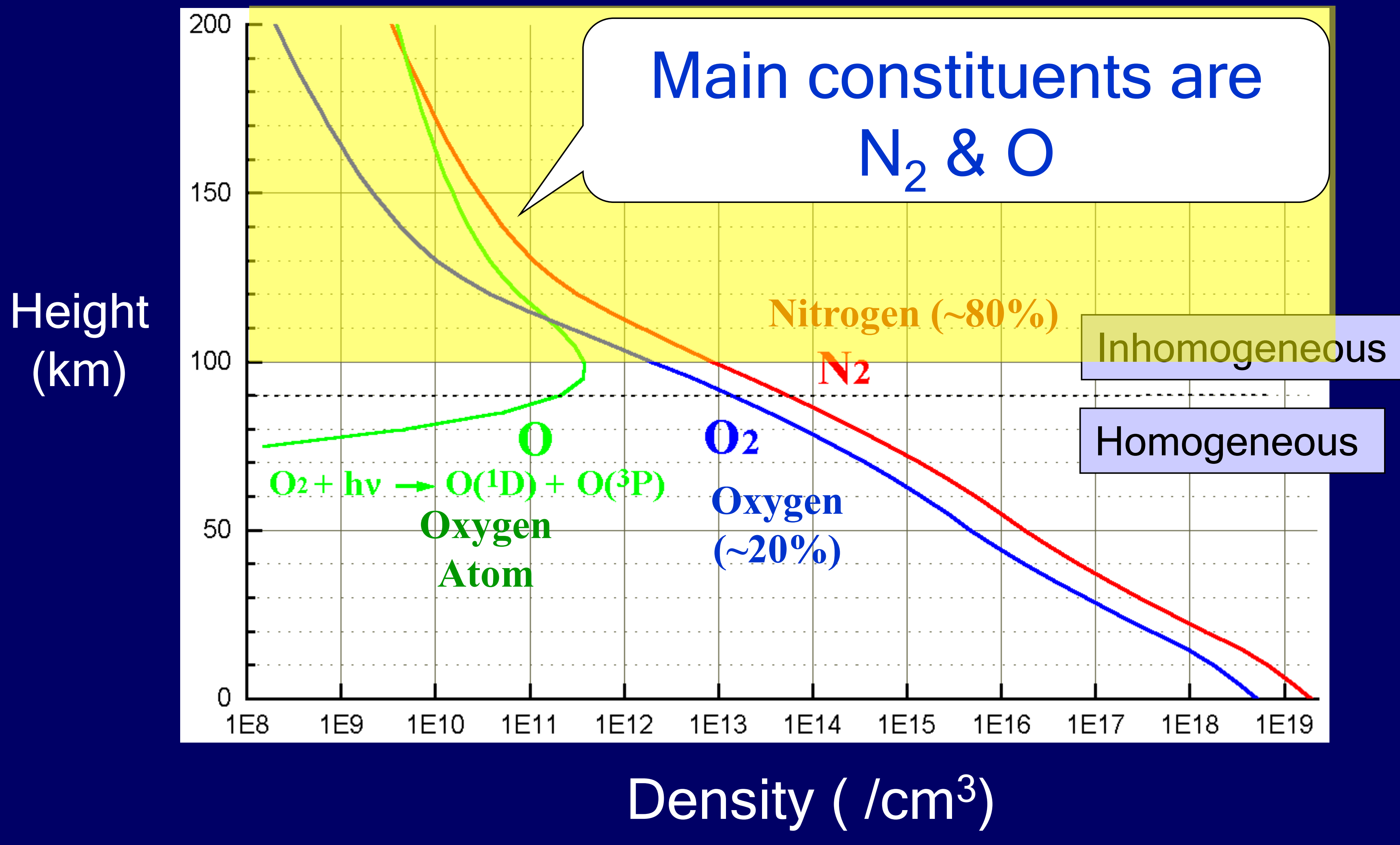


WIC (140～180 nm), CCD

altitude: 7 Re x 1000 km, Δt =2 min

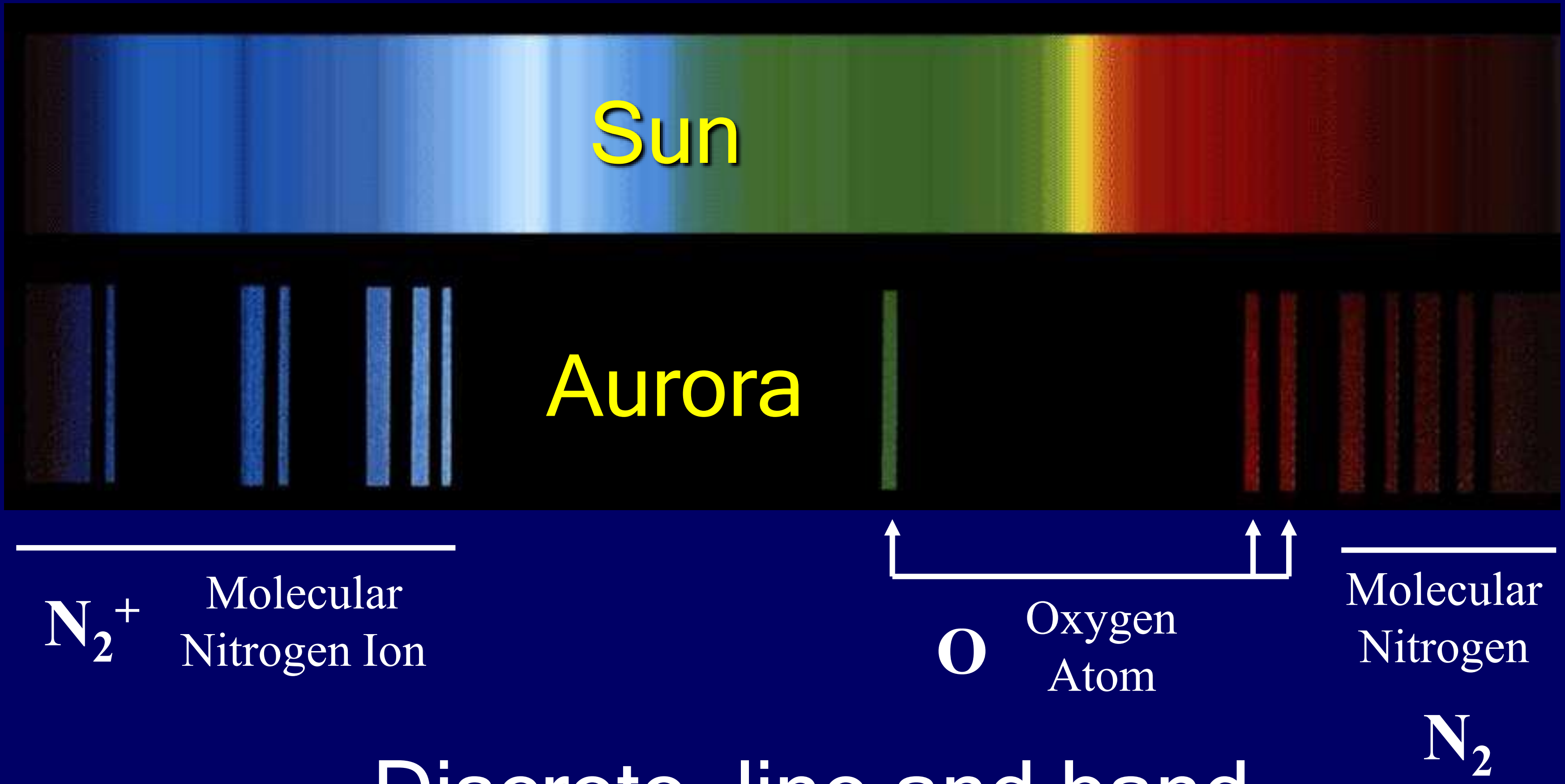
Altitude of Aurora

Emission from what ?



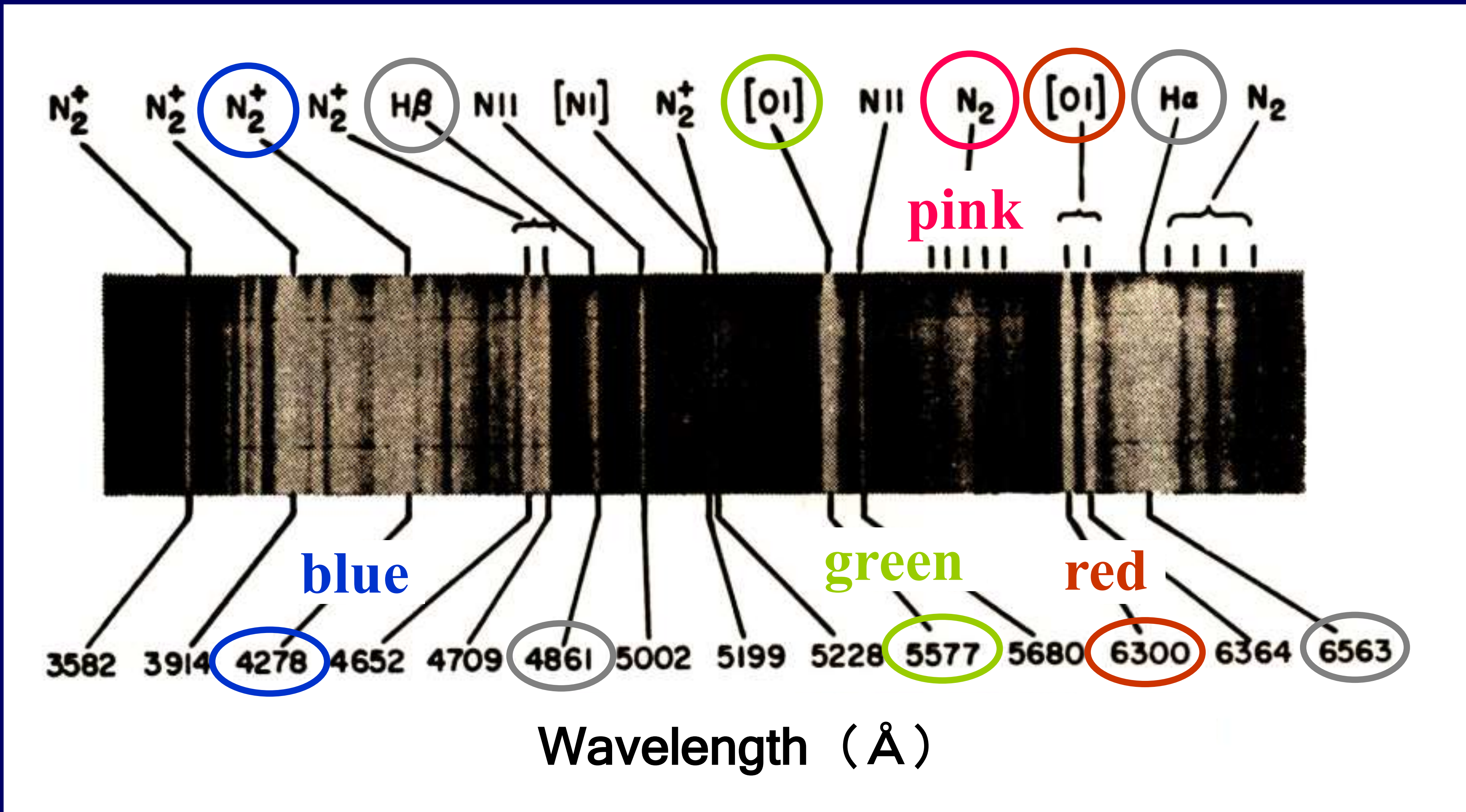
Spectrum of the Aurora

Continuous



Discrete, line and band

Spectrum of Aurora



N_2, N_2^+, N, O, and H

Emission lines in Auroral Spectra

TABLE 5.4

EMISSIONS IDENTIFIED IN AURORAL SPECTRA
ARRANGED ACCORDING TO WAVELENGTH

An asterisk after the wavelength indicates an identification that is uncertain or questionable because of blending with or obscuration by other features or because there are too few lines or bands in the same transition array or progression to make the identification convincing. Additional features, usually quite weak, have been observed, but have received no satisfactory identification.

λ (A)	Atom or Molecule	Multiplet or band	λ (A)	Atom or molecule	Multiplet or band
2972.325	[OI]	Transauroral	3857.18*	OII	13
3116.7	N_2	2P(3-2)	3857.9	N_2^+	1N(2-2)
3136.0	N_2	2P(2-1)	3872.45*	OII	11
3159.3	N_2	2P(1-0)	3875.82*	OII	13
3192. *	N_2	VK(4-11)	3882.45*	OII	11
3198.	N_2	VK(1-9)	3883.15*	OII	12
3268. *	N_2	VK(2-10)	3884.3	N_2^+	1N(1-1)
3268.1*	N_2	2P(4-4)	3912.0*	OII	17
3285.3	N_2	2P(3-3)	3914.4	N_2^+	1N(0-0)
3309.	N_2	2P(2-2)	3919.287*	OII	17
3339.	N_2	2P(1-1)	3943.0	N_2	2P(2-5)
3371.3	N_2	2P(0-0)	3945.048*	OII	6
3425.	N_2	VK(1-10)	3947.5	OI	3
3466.4	[NI]	Transauroral	3948. *	N_2	VK(4-14)
3469. *	N_2	2P(3-4)	3954.372	OII	6
3500.5*	N_2	2P(2-3)	3955.851	NII	6
3502. *	N_2	VK(2-11)	3973.263	OII	6
3536.7	N_2	2P(1-2)	3978.	N_2	VK(1-12)
3548.9	N_2^+	1N(3-2)	3982.719	OII	6
3563.9	N_2^+	1N(2-1)	3994.996	NII	12
3576.9	N_2	2P(0-1)	3998.4	N_2	2P(1-4)
3582.1	N_2^+	1N(1-0)	4026.080	NII	40
3602.	N_2	VK(0-10)	4035.087	NII	39
3671.9	N_2	2P(3-5)	4041.321	NII	39
3683.	N_2	VK(1-11)	4043.537	NII	39
3692.44	OI	6	4044.75*	NII	39
3710.5	N_2	2P(2-4)	4045. *	N_2	VK(5-15)
3712.75*	OII	3	4057.00*	NII	39
3726.16	[OII]	Nebular	4059.4	N_2	2P(0-3)
3727.33*	OII	3	4069.8	OII	10
3728.91	[OII]	Nebular	4072.164	OII	10
3749.49	OII	3	4072.	N_2	VK(2-13)
3755.4	N_2	2P(1-3)	4075.868	OII	10
3767.	N_2	VK(2-12)	4078.862*	OII	10
3804.9	N_2	2P(0-2)	4092.940*	OII	10
3835.4*	N_2^+	1N(3-3)	4094.8*	N_2	2P(4-8)

TABLE 5.4 (*cont.*)

λ (A)	Atom or molecule	Multiplet or band	λ (A)	Atom or molecule	Multiplet or band
4110.9*	N_2^+	1N(6-7)	4554.1	N_2^+	1N(3-5)
4112.029*	OII	21	4564.78*	NII	14
4120. *	OII	20	4574.3	N_2	2P(1-6)
4121.3*	N_2^+	1N(5-6)	4590.971*	OII	15
4121.48*	OII	19	4596.174*	OII	15
4141.8	N_2	2P(3-7)	4599.7	N_2^+	1N(2-4)
4151.46*	NI	6	4601.478	NII	5
4166.8	N_2^+	1N(3-4)	4607.153	NII	5
4169. *	N_2	VK(3-14)	4621.392	NII	5
4169.230*	OII	19	4630.537	NII	5
4171.608	NII	43	4638.854	OII	1
4176.164	NII	42	4641.811	OII	1
4185.456	OII	36	4649.139	OII	1
4189.788	OII	36	4650.841	OII	1
4199.1	N_2^+	1N(2-3)	4651.8	N_2^+	1N(1-3)
4218. *	N_2	VK(0-12)	4661.635	OII	1
4223.04*	NI	5	4676.234	OII	1
4236.5	N_2^+	1N(1-2)	4709.2	N_2^+	1N(0-2)
4237.0*	NII	48	4771. *	N_2	VK(5-17)
4241.787	NII	47	4780.5*	NII	20
4241.787	NII	48	4791. *	NII	20
4278.1	N_2^+	1N(0-1)	4810.286*	NII	20
4317.139	OII	2	4837. *	N_2	VK(2-15)
4319.631	OII	2	4861.332	Hβ	1
4320. *	N_2	VK(1-13)	4890.93*	OII	28
4336.865	OII	2	4895.20*	NII	1
4340.468	Hγ	1	4914.90	NI	9
4343.6*	N_2	2P(0-4)	4924.60*	OII	28
4345.562	OII	2	4935.03	NI	9
4347.425	OII	16	4941.12*	OII	33
4349.426	OII	2	4957.9	N_2^+	1N(4-7)
4351.269	OII	16	4968.	OI	14
4368.30	OI	5	4987.377*	NII	24
4369.28*	OII	26	5001.3	NII	19
4414.909	OII	5	5002.692	NII	4
4416.975	OII	5	5005.140	NII	19
4425.	N_2	VK(2-14)	5010.620	NII	4
4452.377	OII	5	5016.387	NII	19
4466.6*	N_2^+	1N(6-8)	5025.665	NII	19
4485.9*	N_2^+	1N(5-7)	5045.098	NII	4
4488.15*	NII	21	5076.6	N_2^+	1N(2-5)
4507.559*	NII	21	5148.8	N_2^+	1N(1-4)
4515.9*	N_2^+	1N(4-6)	5198.5	[NI]	Nebular
4534.	N_2	VK(3-15)	5200.7	[NI]	Nebular

Emission lines in Auroral Spectra

TABLE 5.4 (*cont.*)

λ (A)	Atom or molecule	Multiplet or band	λ (A)	Atom or molecule	Multiplet or band
5228.3	N_2^+	1N(0-3)	6482.07	NII	8
5295.7	O_2^+	1N(2-0)	6544.8	N_2	1P(7-4)
5330.	OI	12	6562.817	Hα	1
5436.	OI	11	6583.6•	[NII]	Nebular
5454.26•	NII	29	6623.6	N_2	1P(6-3)
5478.2•	N_2	1P(9-4)	6704.8	N_2	1P(5-2)
5577.345	[OI]	Auroral	6764.0•	N_2	1P(11-9)
5631.9	O_2^+	1N(1-0)	6788.6	N_2	1P(4-1)
5666.64	NII	3	6853.0	N_2^+	Mein.(3-0)
5676.02	NII	3	6859.3•	N_2	1P(10-8)
5679.56	NII	3	6875.2	N_2	1P(3-0)
5686.21	NII	3	6957.7	N_2	1P(9-7)
5710.76	NII	3	7036.8	N_2^+	Mein.(4-1)
5730.67	NII	3	7059.5•	N_2	1P(8-6)
5747.29•	NII	9	7164.8	N_2	1P(7-5)
5752. •	N_2	VK(1-16)	7239.9	N_2^+	Mein.(5-2)
5754.8	[NII]	Auroral	7254.4•	OI	20
5755.2•	N_2	1P(12-8)	7274.0	N_2	1P(6-4)
5767.43•	NII	9	7318.6	[OII]	Auroral
5804.3•	N_2	1P(11-7)	7319.4	[OII]	Auroral
5854.4	N_2	1P(10-6)	7329.9	[OII]	Auroral
5889.953 }	NaI	1	7330.7	[OII]	Auroral
5895.923 }			7349.8•	N_2	1P(11-10)
5906.0•	N_2	1P(9-5)	7387.2	N_2	1P(5-3)
5959.0	N_2	1P(8-4)	7479.0•	N_2	1P(10-9)
5960.93•	NII	28	7504.7	N_2	1P(4-2)
5973.4•	O_2^+	1N(1-1)	7612.9•	N_2	1P(9-8)
6013.6	N_2	1P(7-3)	7626.8	N_2	1P(3-1)
6026.4	O_2^+	1N(0-0)	7684.	O_2	Atm.(1-1)
6046. •	OI	22	7752.0•	N_2	1P(8-7)
6068. •	N_2	VK(3-18)	7753.7	N_2	1P(2-0)
6069.7	N_2	1P(6-2)	7774.	OI	1
6127.4	N_2	1P(5-1)	7825.7	N_2^+	Mein.(2-0)
6157.	OI	10	7896.9•	N_2	1P(7-6)
6185.2•	N_2	1P(12-9)	7987.	OI	19
6186.8•	N_2	1P(4-0)	7995.12	OI	19
6253.0•	N_2	1P(11-8)	8047.9•	N_2	1P(6-5)
6300.308	[OI]	Nebular	8053.6	N_2^+	Mein.(3-1)
6322.9•	N_2	1P(10-7)	8184.80	NI	2
6363.790	[OI]	Nebular	8187.95	NI	2
6394.7	N_2	1P(9-6)	8205.5•	N_2	1P(5-4)
6418.7•	O_2^+	1N(0-1)	8216.28	NI	2
6455. •	OI	9	8223.07	NI	2
6468.5	N_2	1P(8-5)	8242.34	NI	2

TABLE 5.4 (*cont.*)

λ (A)	Atom or molecule	Multiplet or band	λ (A)	Atom or molecule	Multiplet or band
8293.4	N_2^+	Mein.(4-2)	9145.3	N_2^+	Mein.(1-0)
8446.5	OI	4	9431.2•	N_2^+	Mein.(2-1)
8542.5	N_2	1P(3-2)	10,395.4	[NI]	Auroral
8598.	O_2	Atm.(0-1)	10,404.1	[NI]	Auroral
8629.24	NI	8	10,510.	N_2	1P(0-0)
8680.24	NI	1	10,830. •	HeI	1
8683.38	NI	1	11,036.2	N_2^+	Mein.(0-0)
8703.24	NI	1	11,820.2•	N_2^+	Mein.(2-2)
8711.69	NI	1	14,523.	N_2^+	Mein.(0-1)
8718.82	NI	1	14,663. •	O_2	IR Atm.(0-1)
8723.0	N_2	1P(2-1)	15,114.	N_2^+	Mein.(1-2)
8912.4	N_2	1P(1-0)	15,748.	N_2^+	Mein.(2-3)
9060.6•	NI	15			

5.1.2. Forbidden Atomic Lines[2]

Oxygen—The strongest emission in the visible region is ordinarily the $[OI]_{32}$ yellowish-green line, first measured by Ångström [1868*a*, 1869*a*] and soon after confirmed by Struve [1869*a*] and many others. Ångström and others found the green line to be present even when visible auroral structure was not, but it was many years before the existence of the airglow was firmly established (see Section 9.1.2).

Precise measurement of the green-line wavelength was first accomplished by Babcock [1923*a*] with an interferometer. Measurements by Cabannes and Dufay [1955*a*] give the wavelength as 5577.345 ± 0.003 A. Production of the green line in the laboratory by McLennan and Shrum [1925*a*] eventually led to the identification of the green line as the $[OI]_{32}$ transition (see the discussion in Section 9.1.2).

The $[OI]_{31}$ line at 2972.325 A (Sayers and Emeleus [1950*a*]) should have a photon intensity of about one sixteenth that for λ5577 $[OI]_{32}$. Because of ozone absorption it is not observable from the ground.

Zöllner [1870*a*] made the first measurement of the red line of $[OI]_{21}$ at 6300 A. The wavelengths of the two lines given in Table 5.1 are from the interferometer measurements of Cabannes and Dufay [1955*a*, *b*, 1956*a*, *b*]. The identification was made by Frerichs [1930*a*], who computed the energy levels from observations of the ultraviolet spectrum

[2] A summary of the transition probabilities, lifetimes, and energy levels associated with oxygen and nitrogen forbidden lines is given in Appendix VI. The spectroscopic nomenclature is discussed in Section 1.1.2.

Emission lines of oxygen atom (OI)

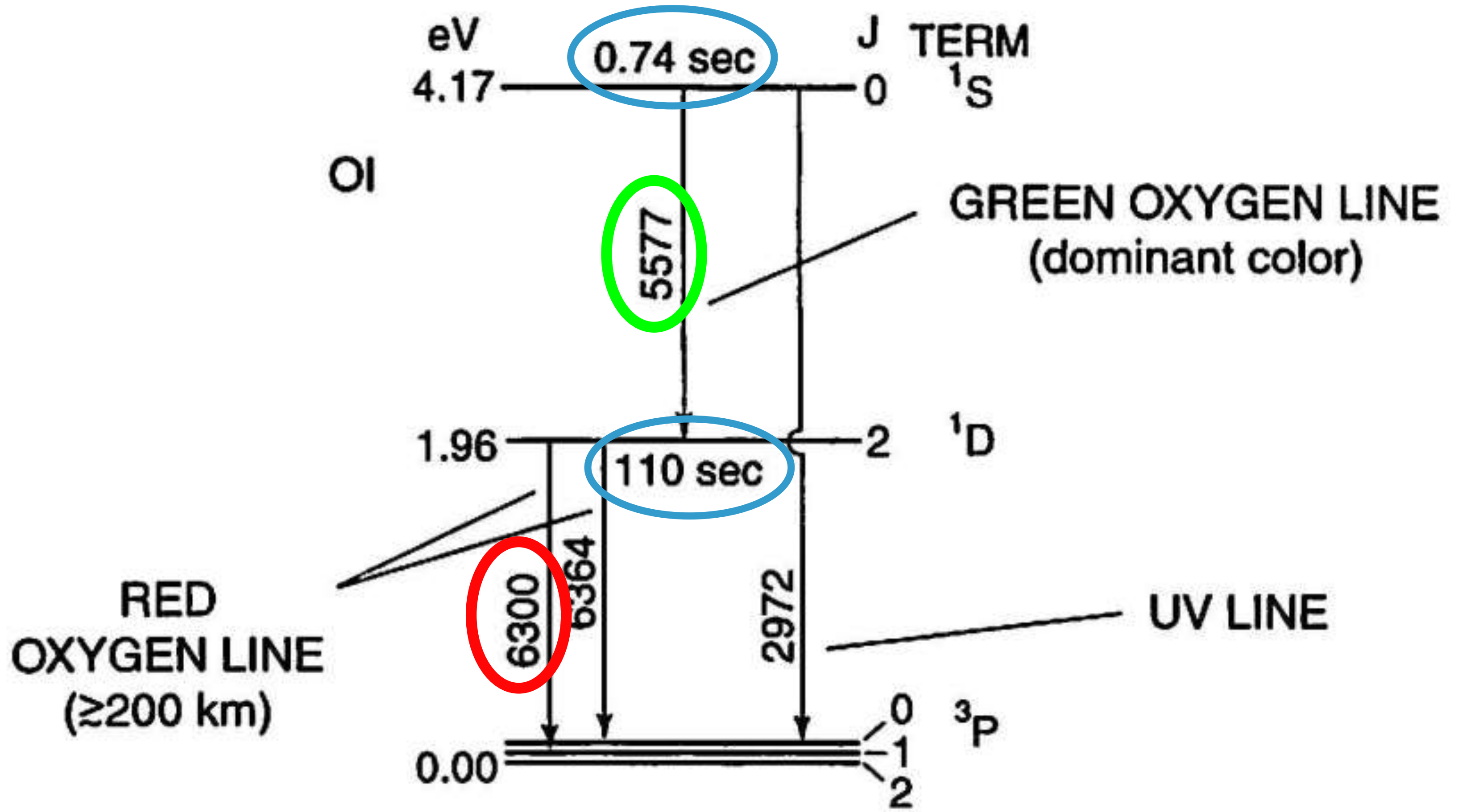


Figure 1.3. Excited states of the oxygen atom that give rise to forbidden transitions prominent in auroral emissions, and their lifetimes (after Roach and Smith, 1967).

Emission lines of nitrogen molecule (N_2)

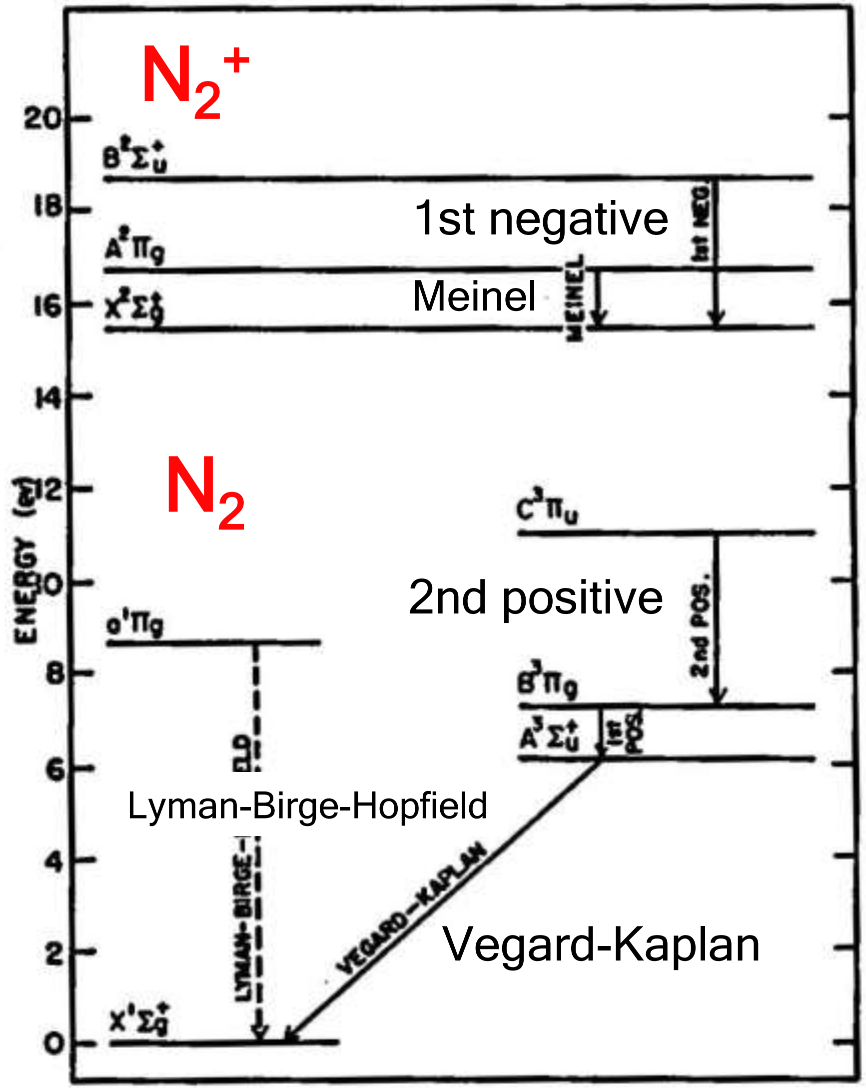
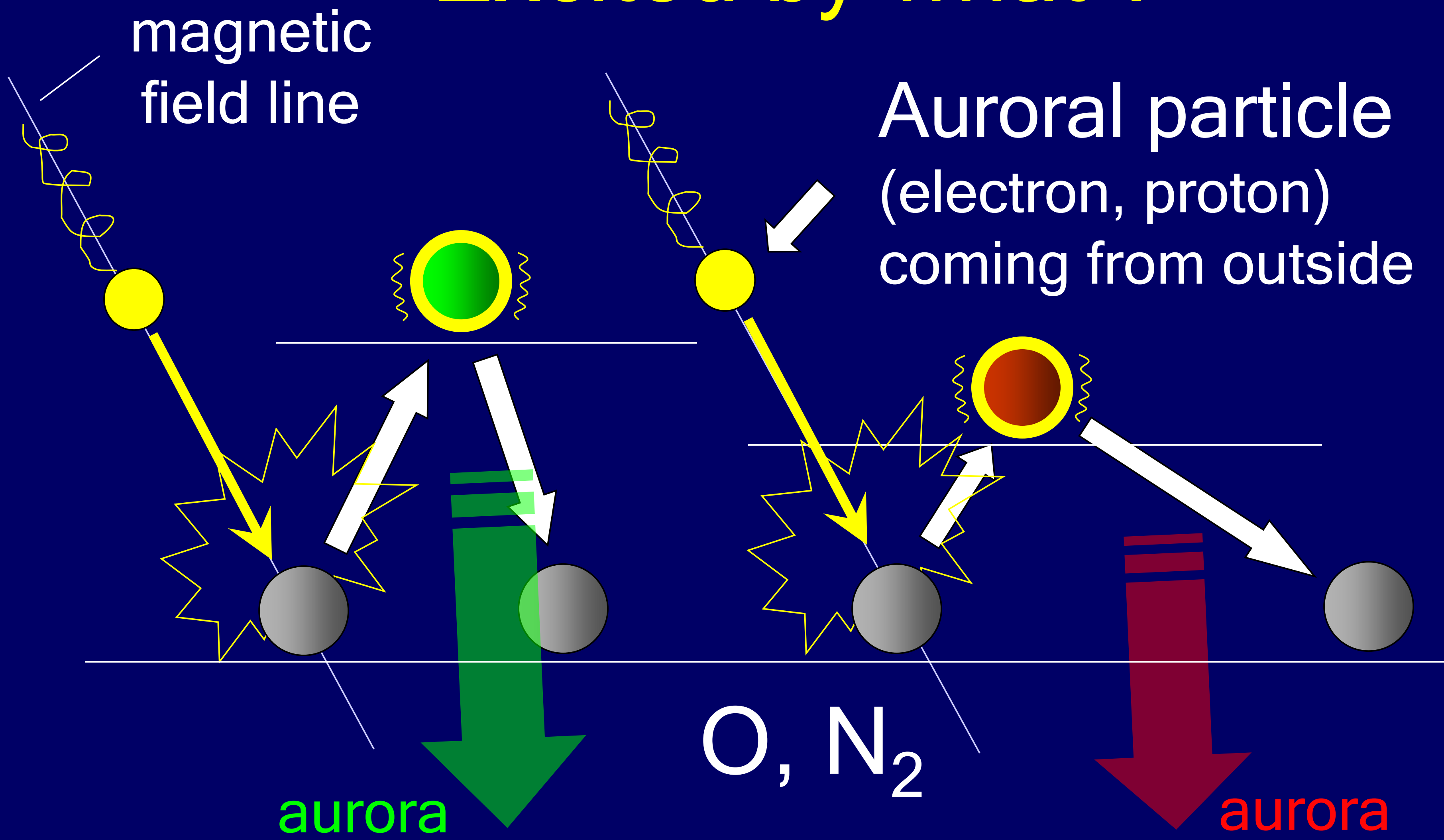


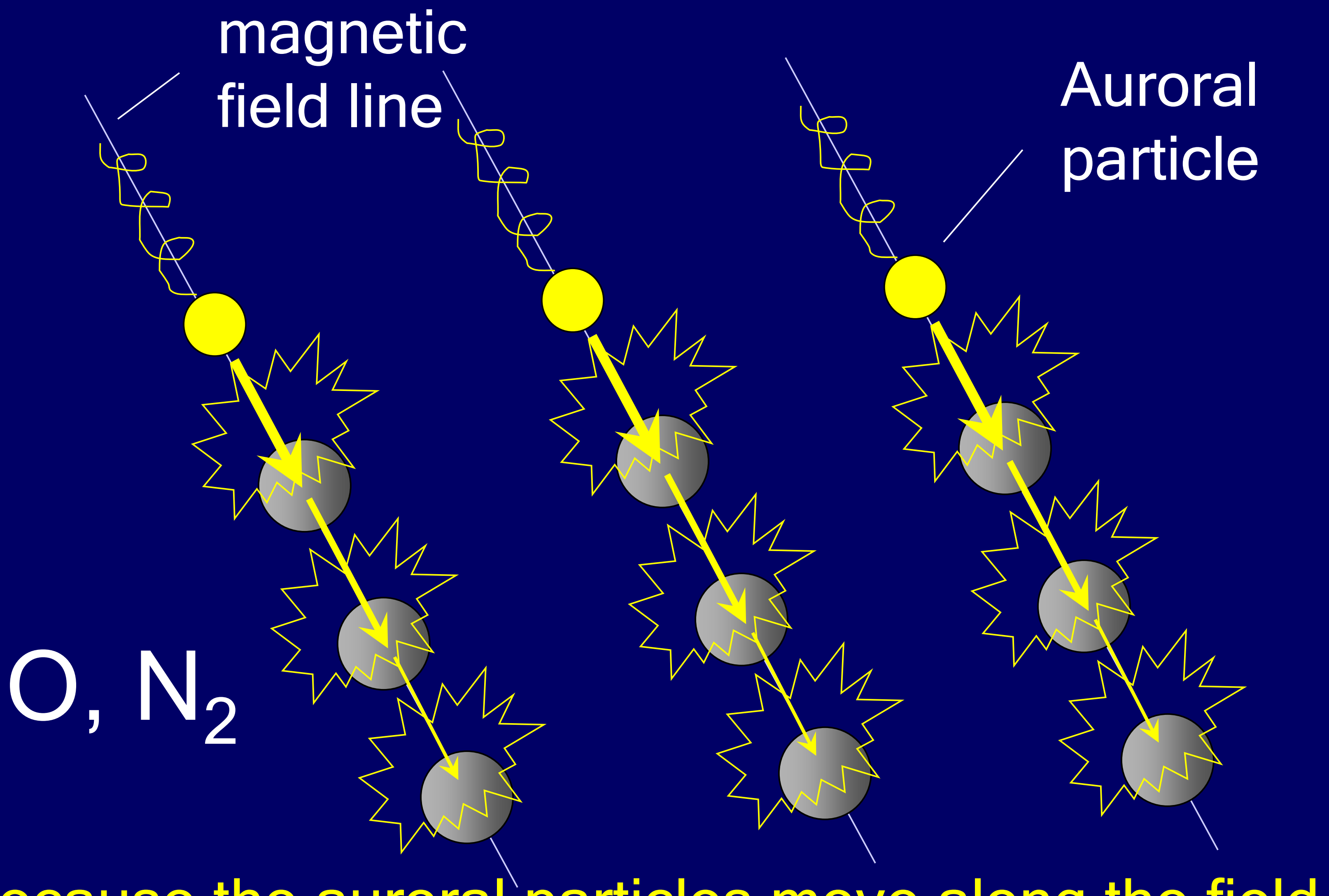
FIG. 5.32. Electronic states and band systems of N_2 and N_2^+. The dashed transition lies in the far ultraviolet and has not been detected in aurora.

Excited by what ?



High energy (several 100eV～10keV) auroral particles collide with the atmosphere, and excite them.

Why the curtain-like form appears ?



Because the auroral particles move along the field line, colliding sequentially until they stop.

Height profile of ionization by precipitated electrons

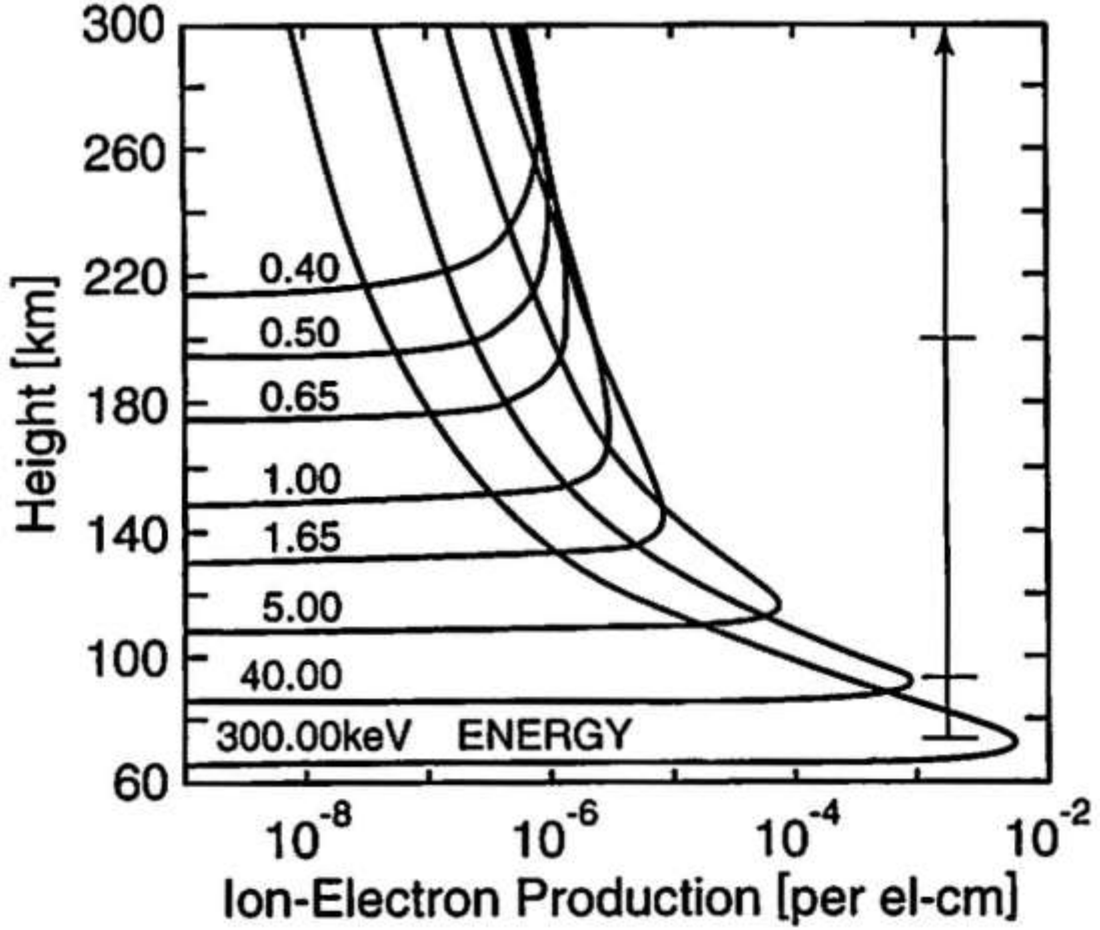
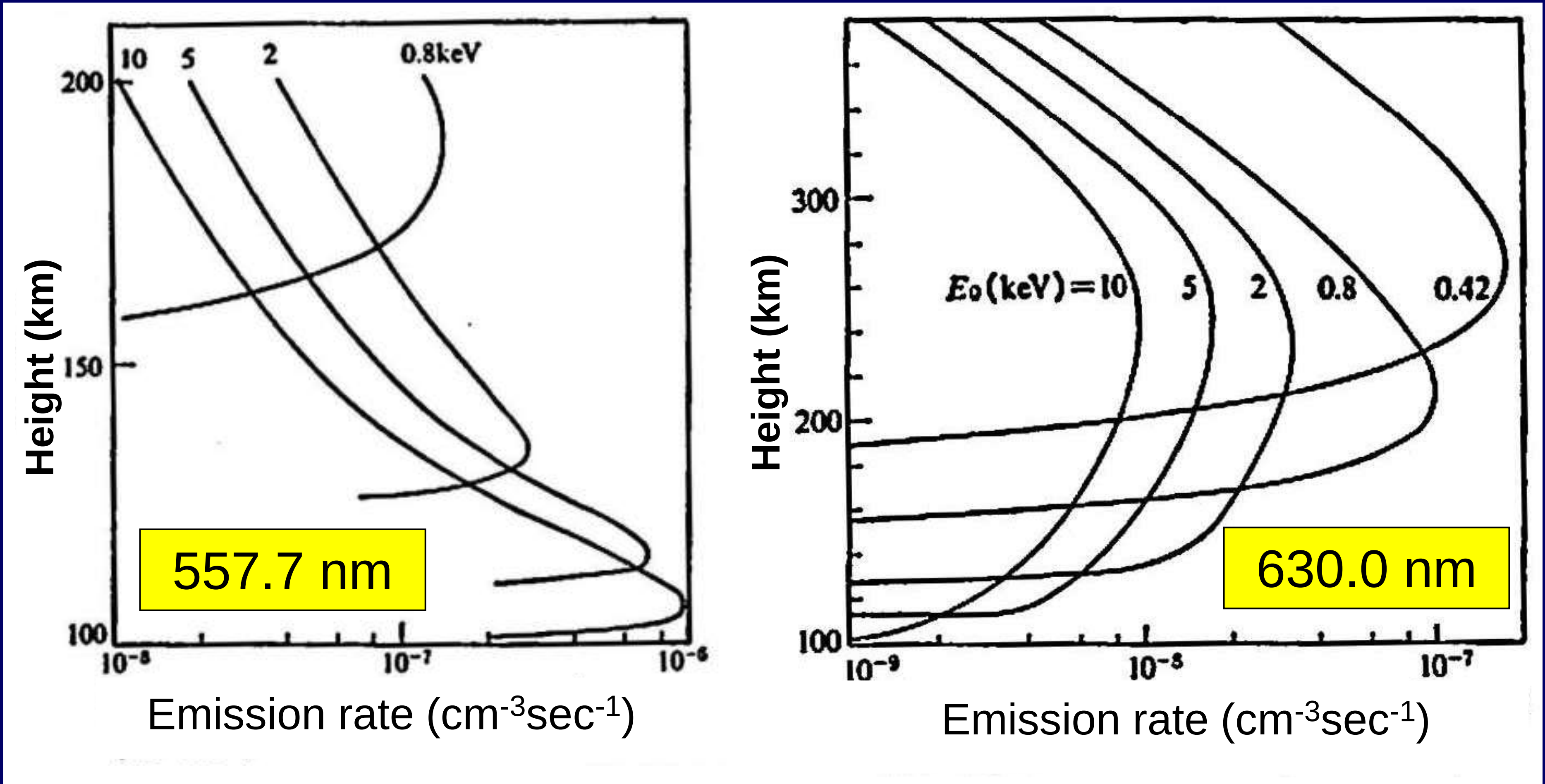


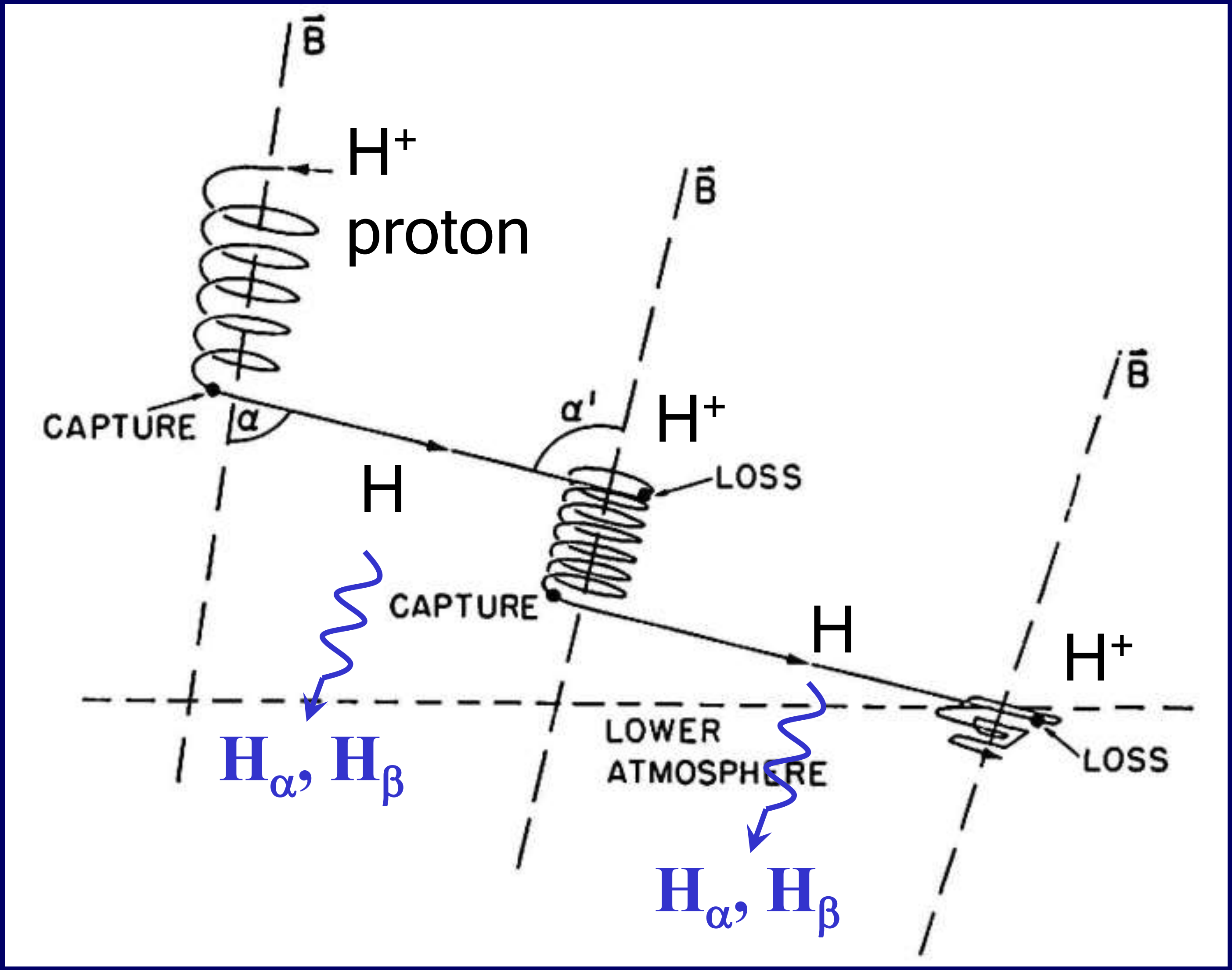
Figure 1.4. Production of ion-electron pairs per unit path length of primary electrons with various initial energies. After Rees (1963).

Height profile of emission rate by precipitated electrons



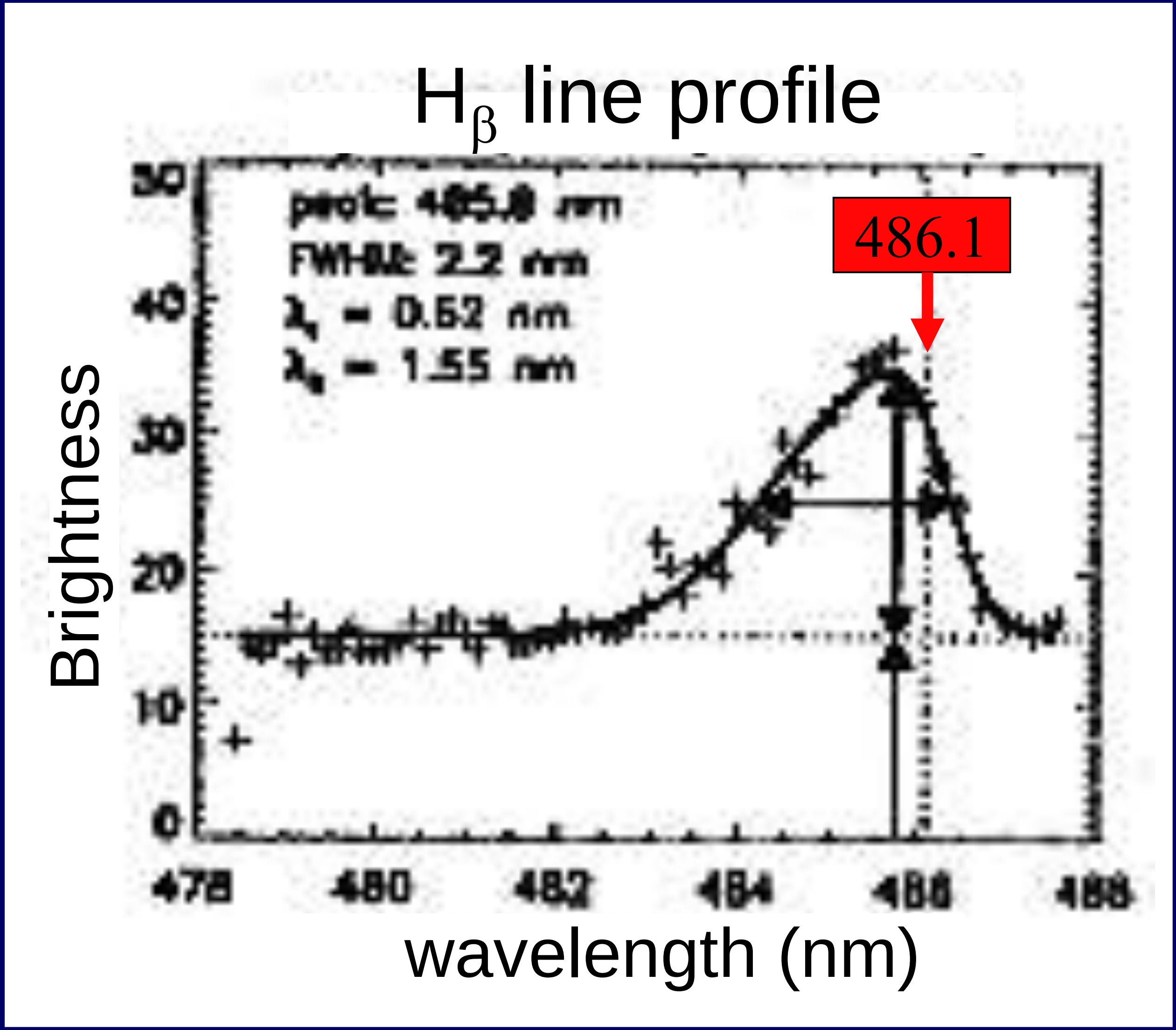
Quenching is effective at lower altitudes for 630.0 nm, because its life time is so long (110 sec).

Proton Aurora



Spatially spread ⇒ diffuse type

Spectrum of Proton Aurora



Doppler broadening and shifting

Height profile of ionization by precipitated protons

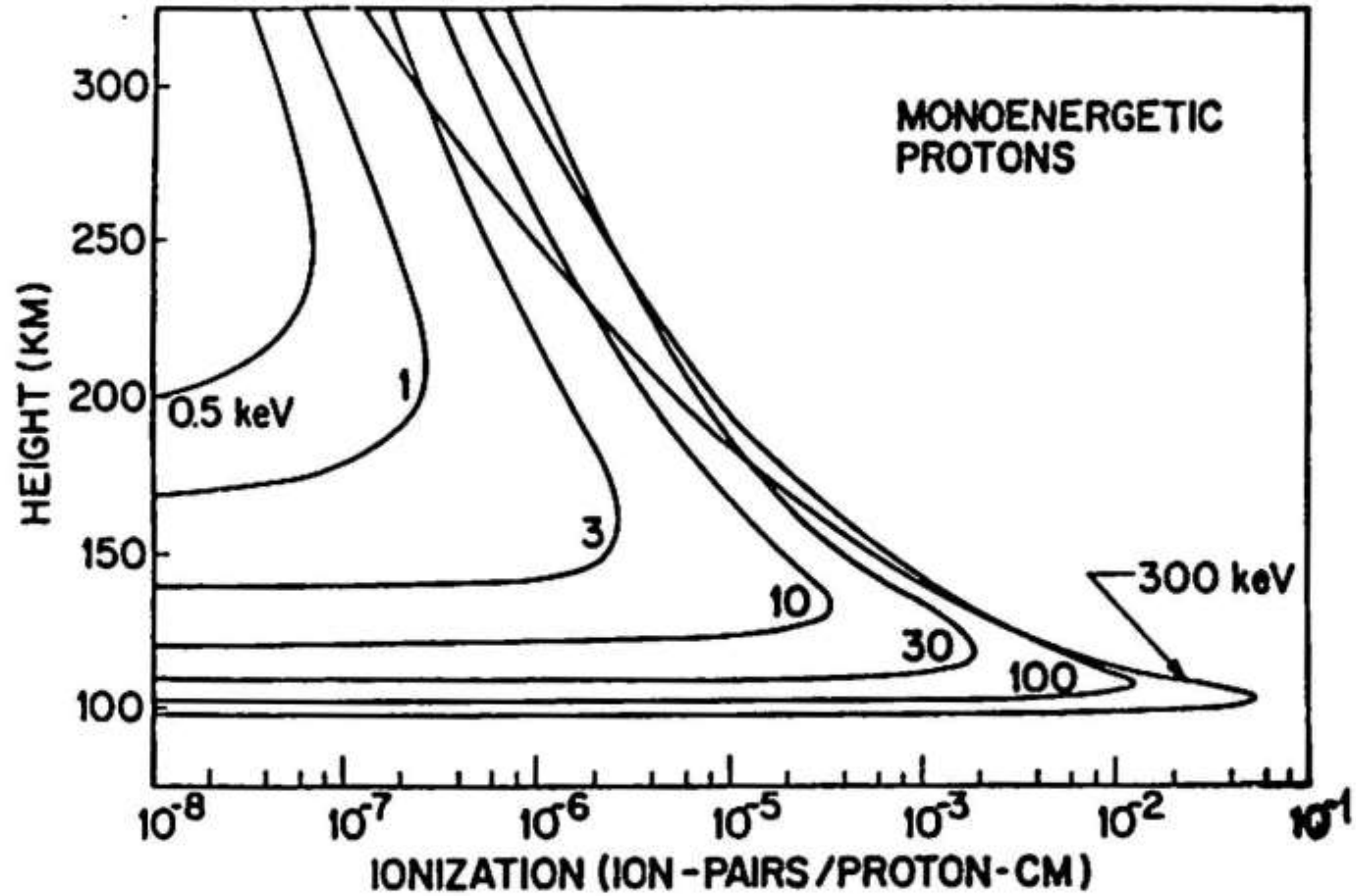
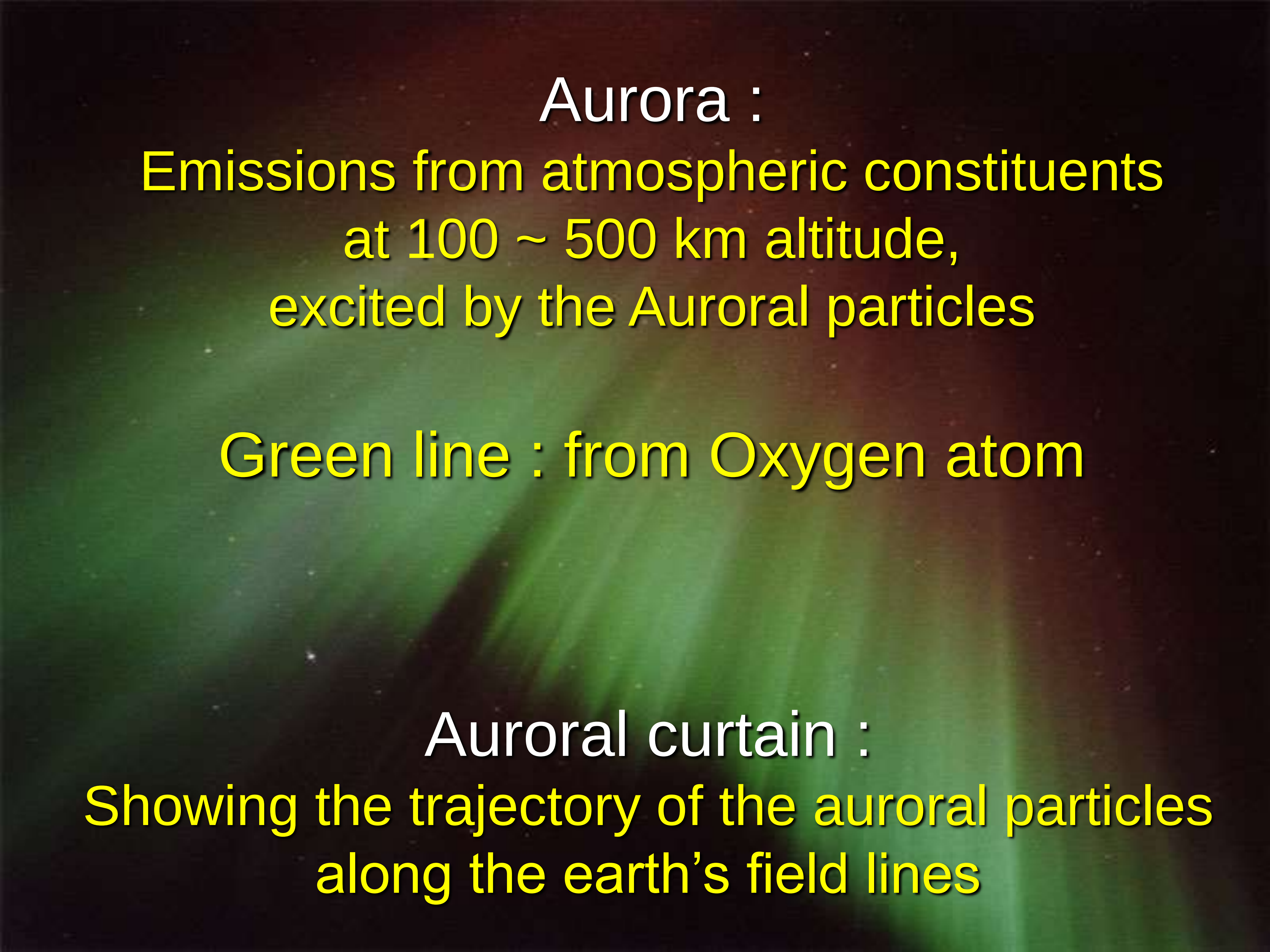


Fig. 4.38. Height profiles for ionization produced by monoenergetic protons with an isotropic pitch angle distribution by Eather (1970). (Courtesy *Annales de Géophysique*.)


Aurora :
Emissions from atmospheric constituents
at 100 ~ 500 km altitude,
excited by the Auroral particles
Green line : from Oxygen atom
Auroral curtain :
Showing the trajectory of the auroral particles
along the earth’s field lines


Red : from Oxygen atom
Pink : from Molecular Nitrogen

The Red Aurora : from Oxygen atom

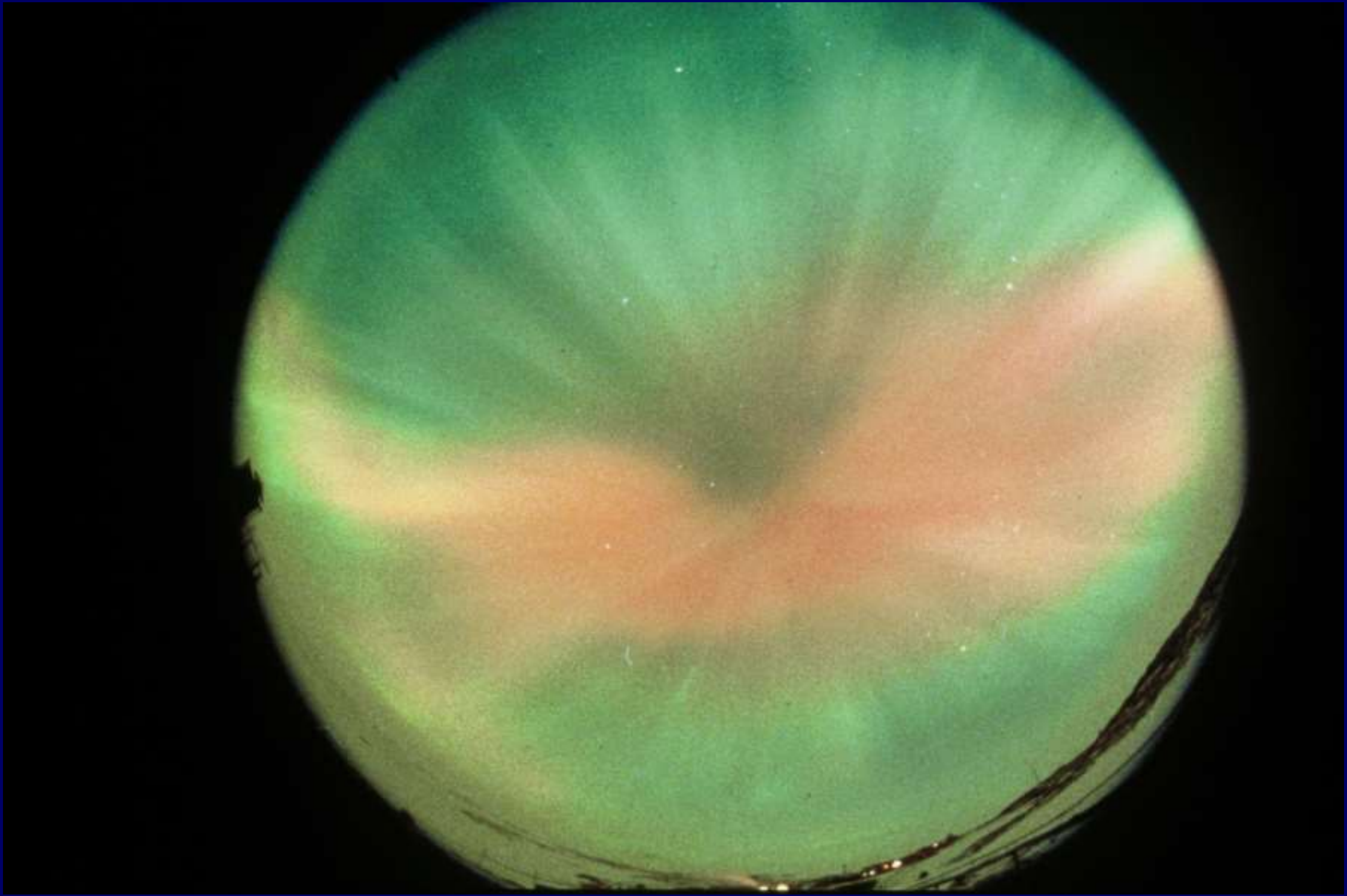
Blue, purple : Molecular Nitrogen

Lower viewing angle ...

Higher viewing angle ...

Looking up along the earth’s magnetic field line ....

Corona



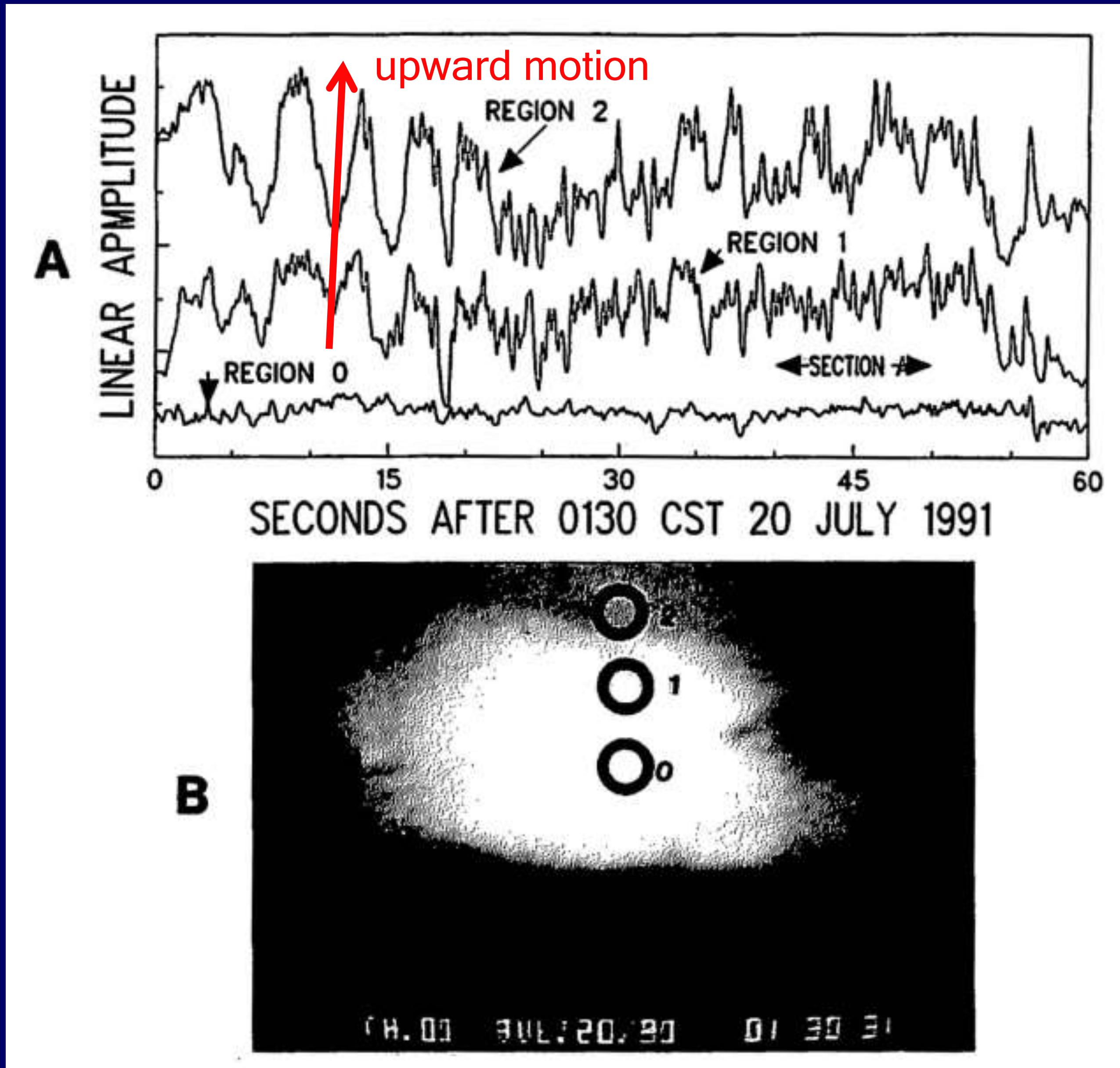
Large scale vortex : Spiral


Spiral

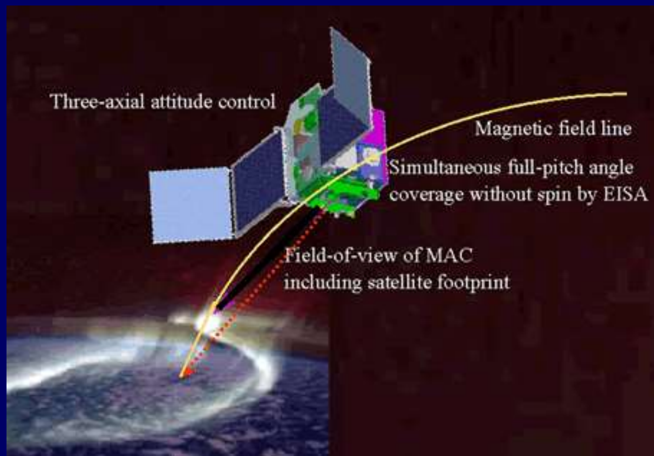

Diffuse Aurora
Black Aurora
Pulsating Aurora


Diffuse Aurora
Black Aurora
Pulsating Aurora

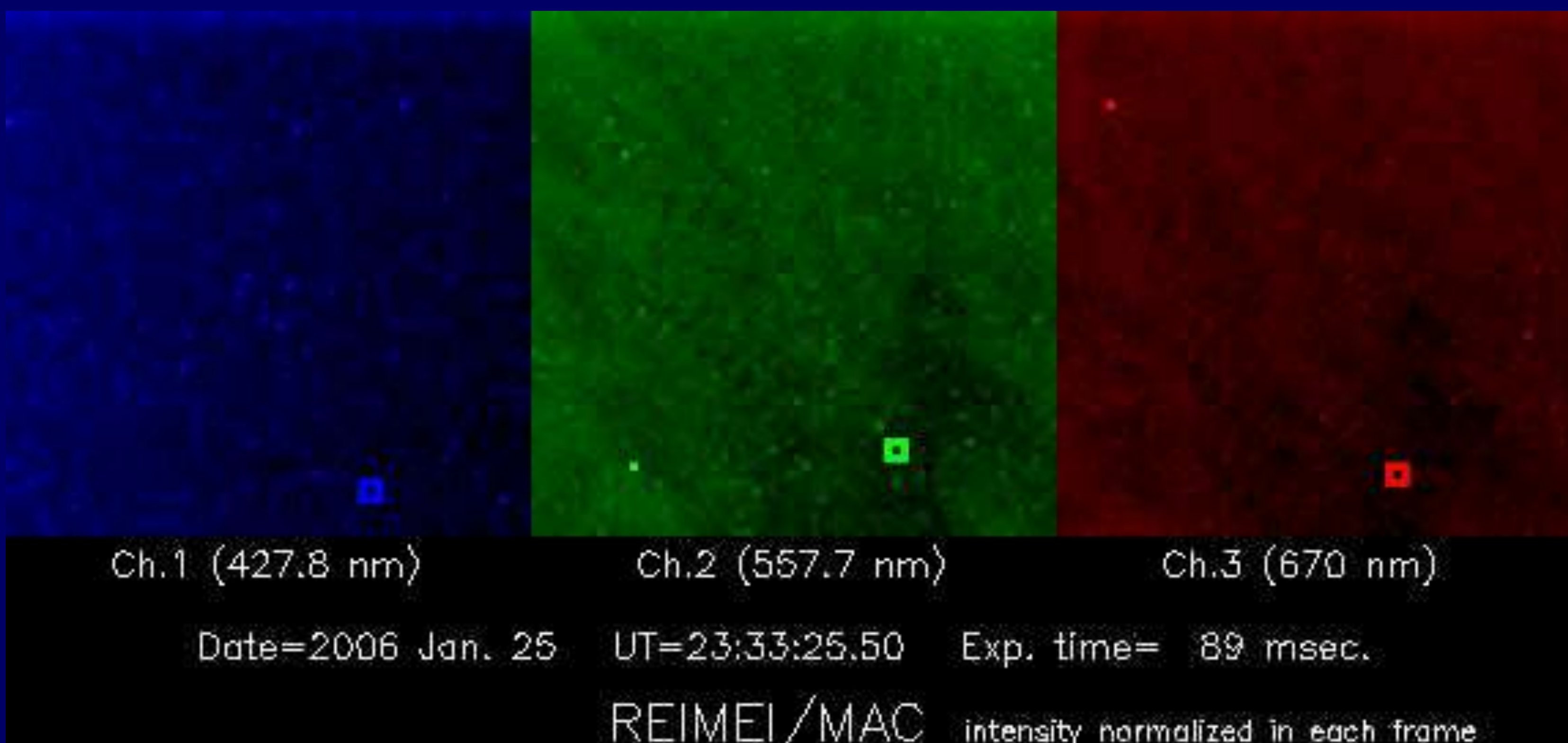
Pulsating Aurora



Pulsating Aurora observed by REIMEI



Japanese small satellite
launched on 24 Aug, 2005
altitude: 610 km
instrument : MAC, ESA/ISA
high spatial & time resolution



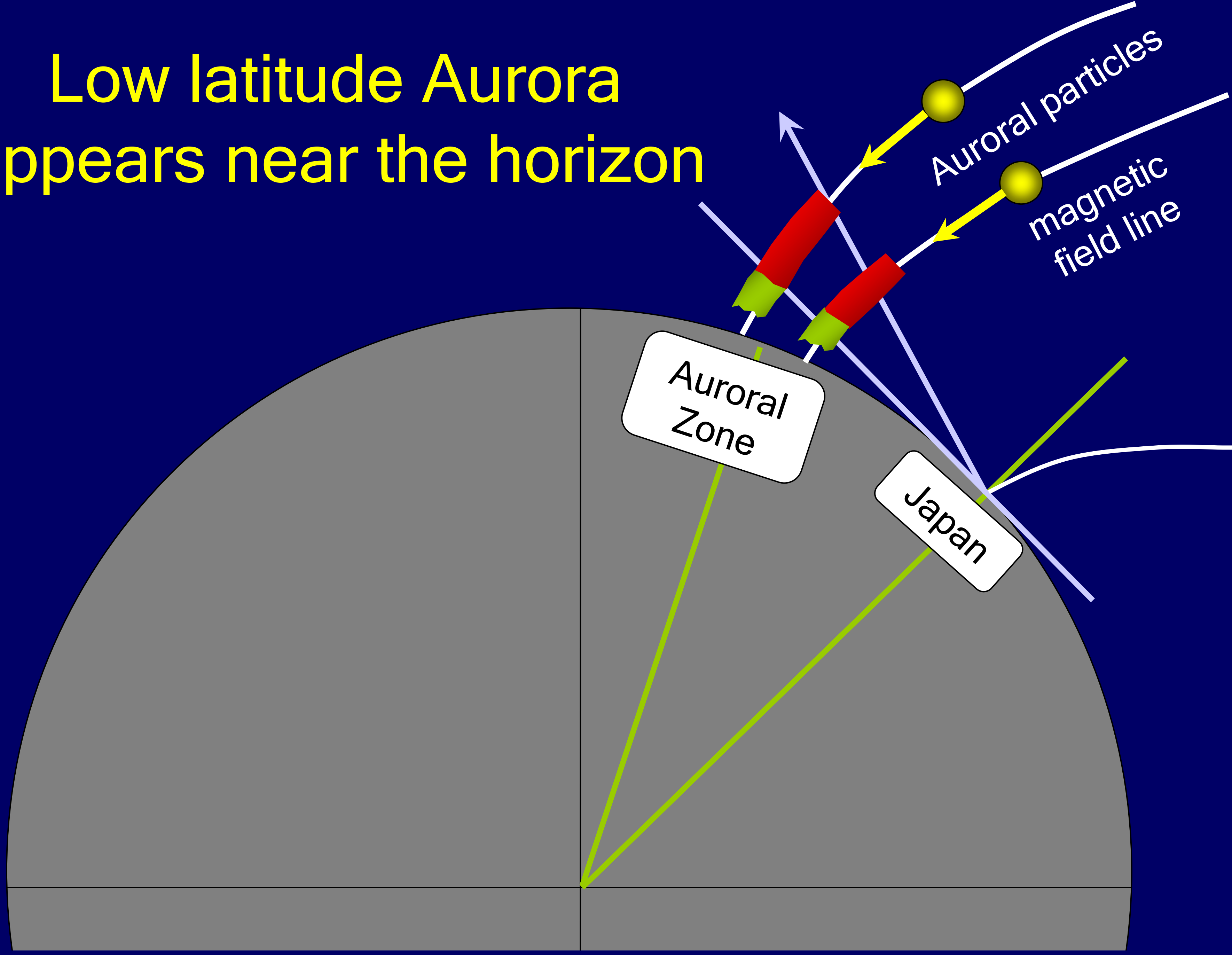
Low-latitude Red Aurora : from Oxygen atom

Low latitude Aurora appears during a large storm-time

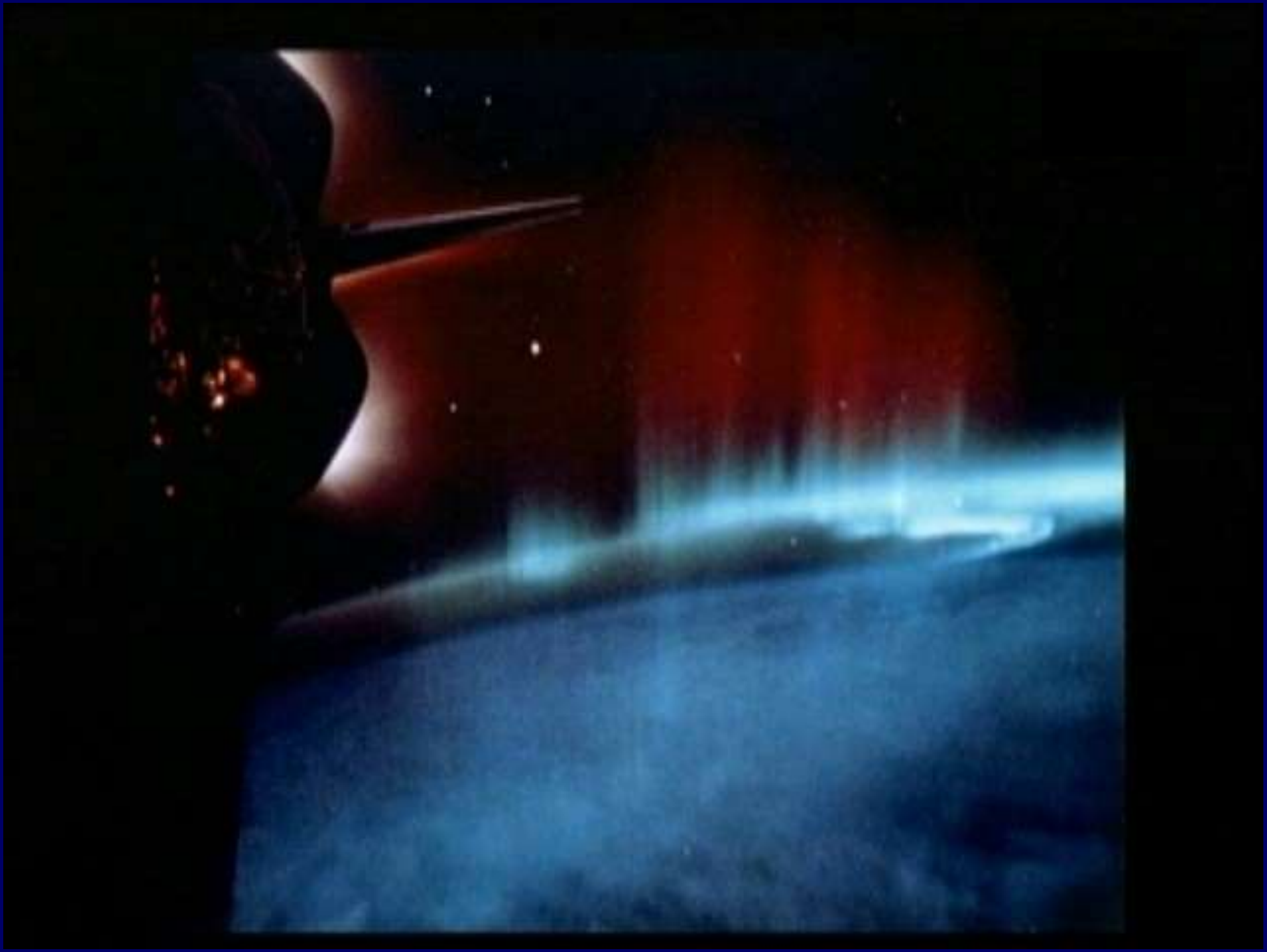
22 Oct, 1989

29 Oct., 2003

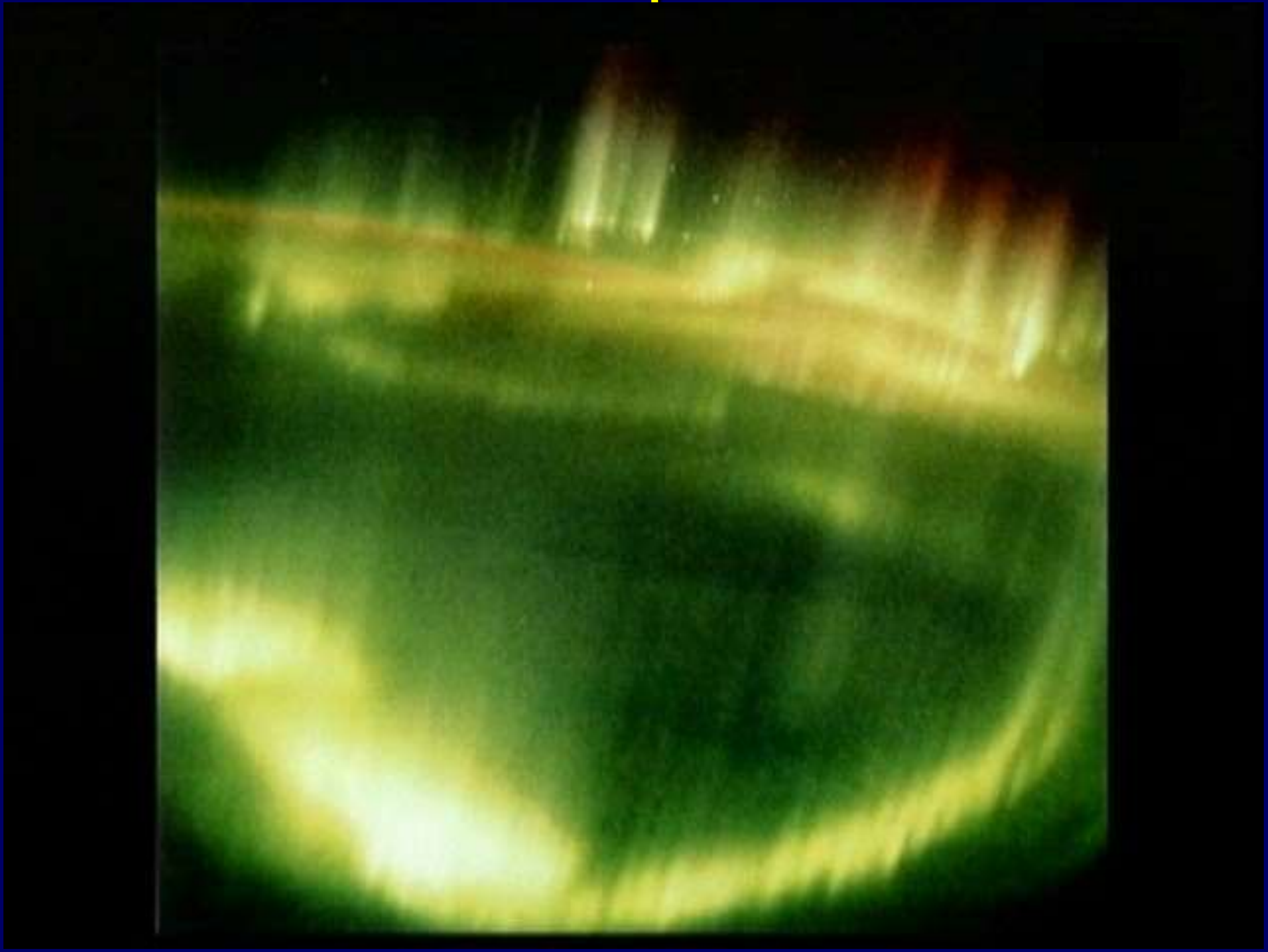
Low latitude Aurora appears near the horizon



Aurora from Space Shuttle

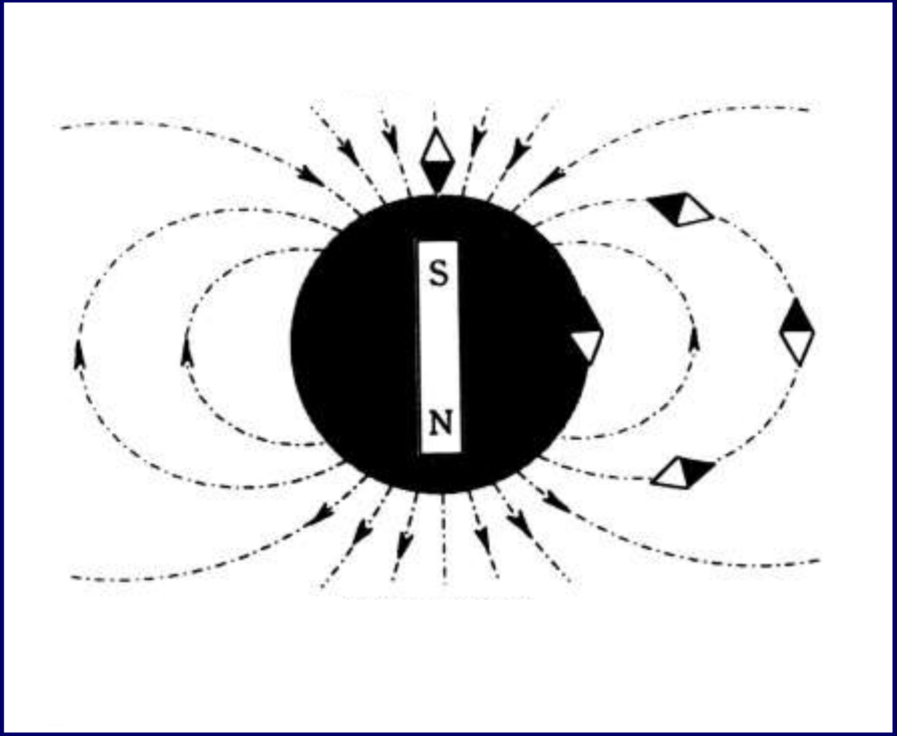


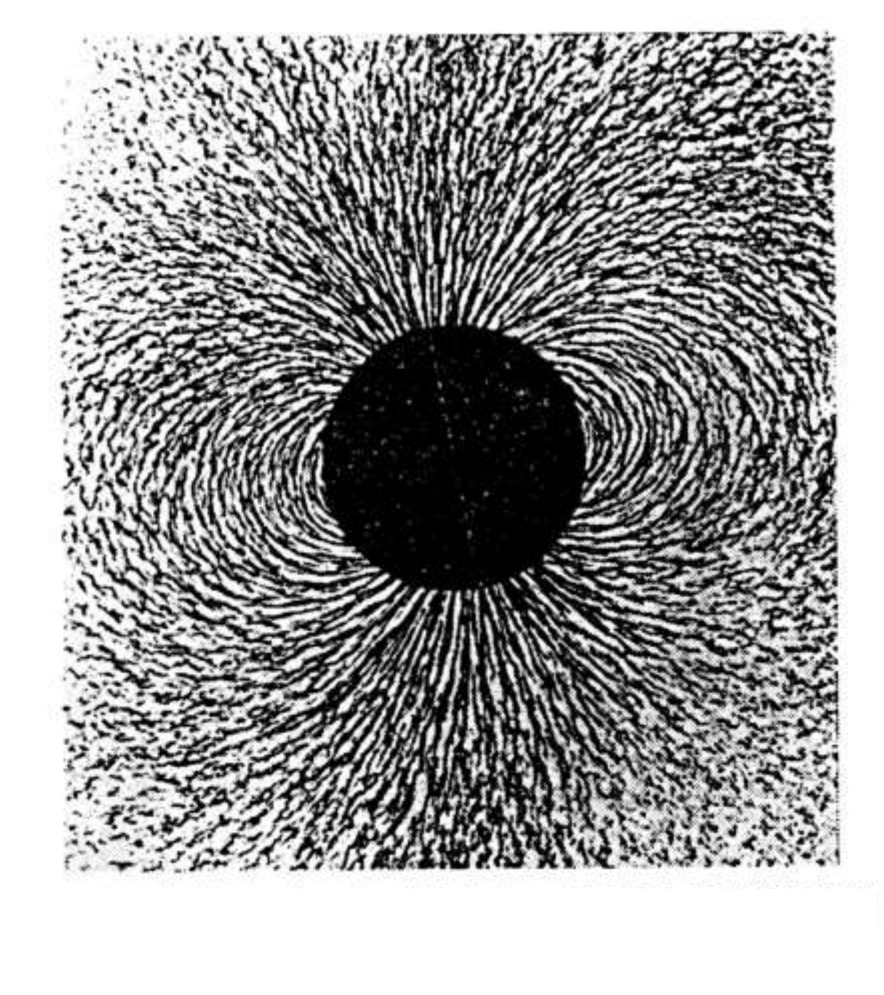
Aurora from Space Shuttle



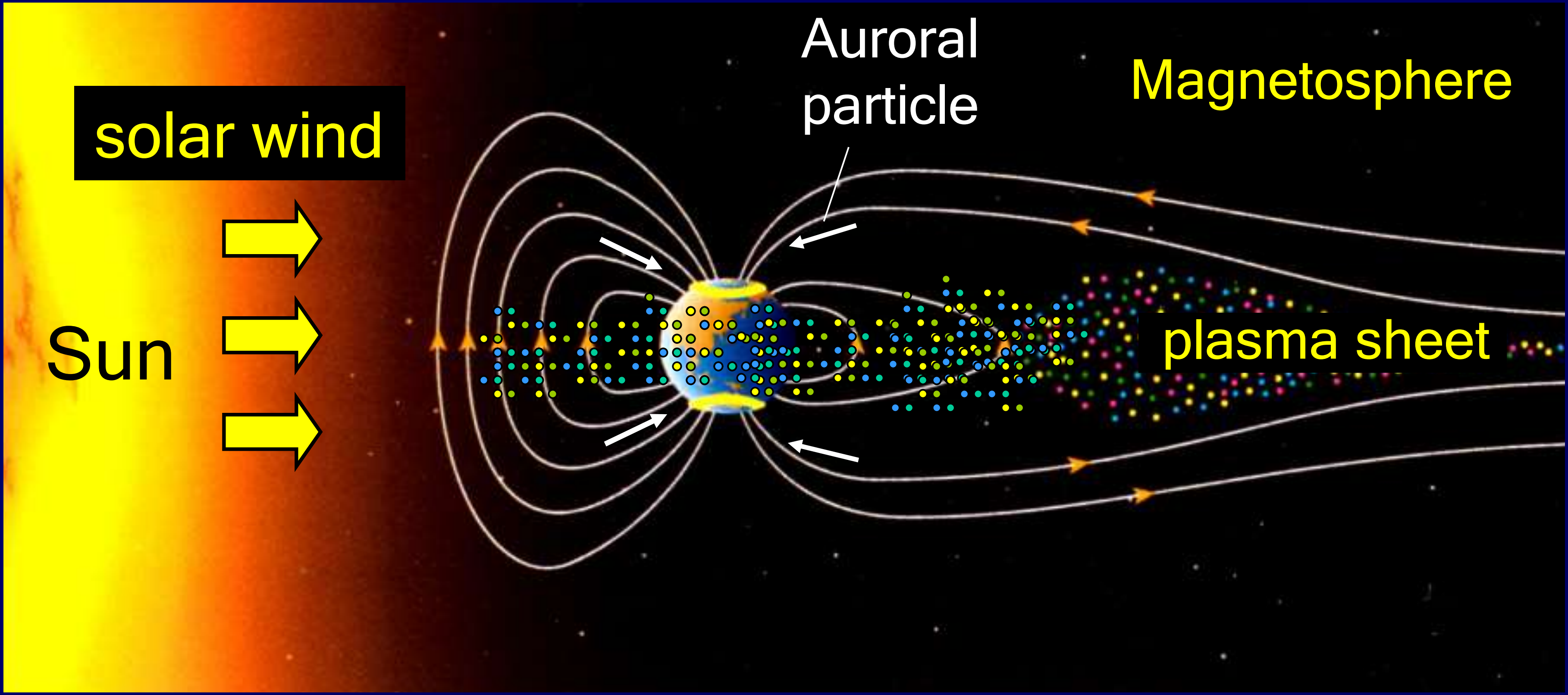

Where auroral particles come from ?

Earth's magnetic field



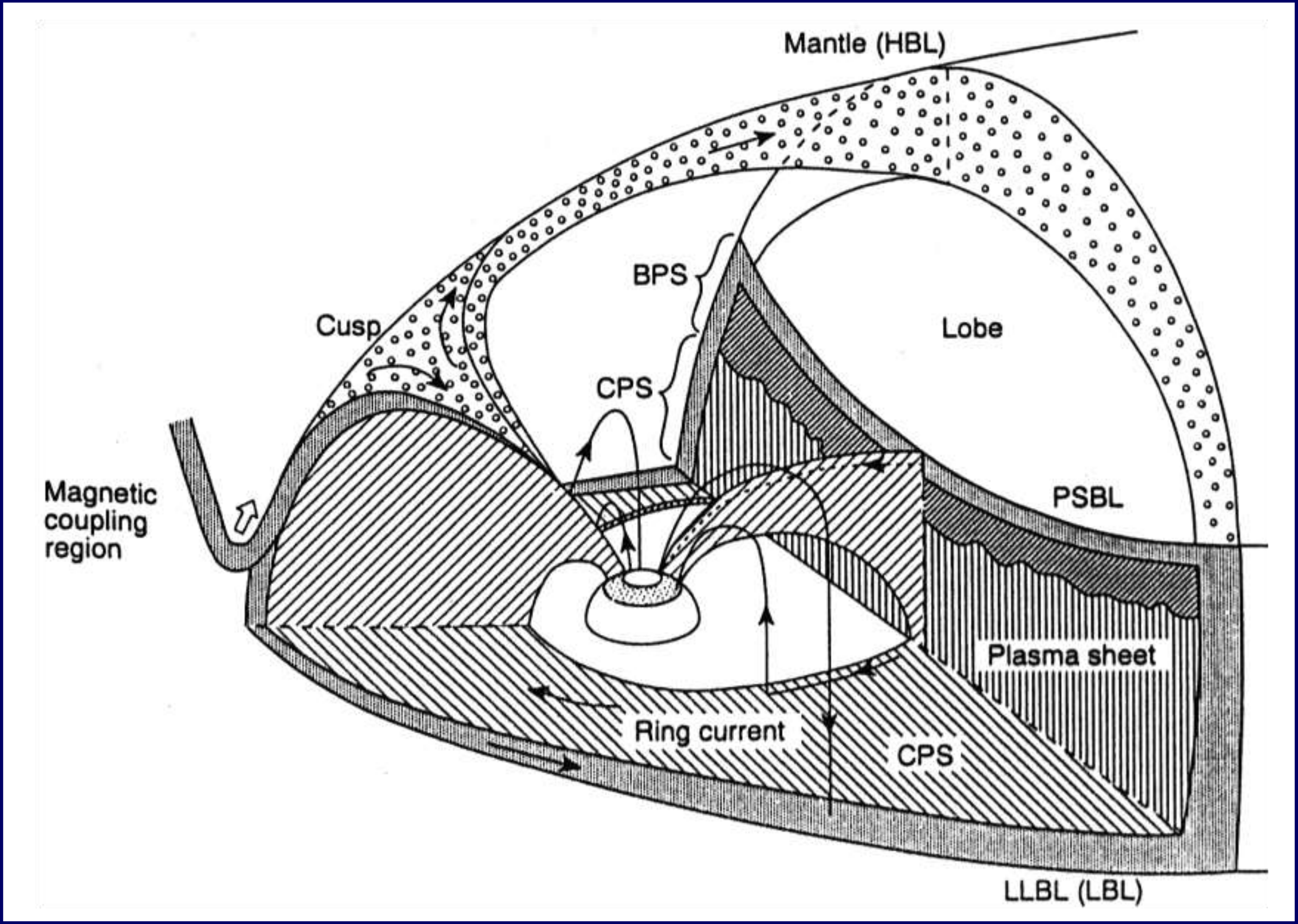


Magnetosphere
territory of the earth's magnetic field

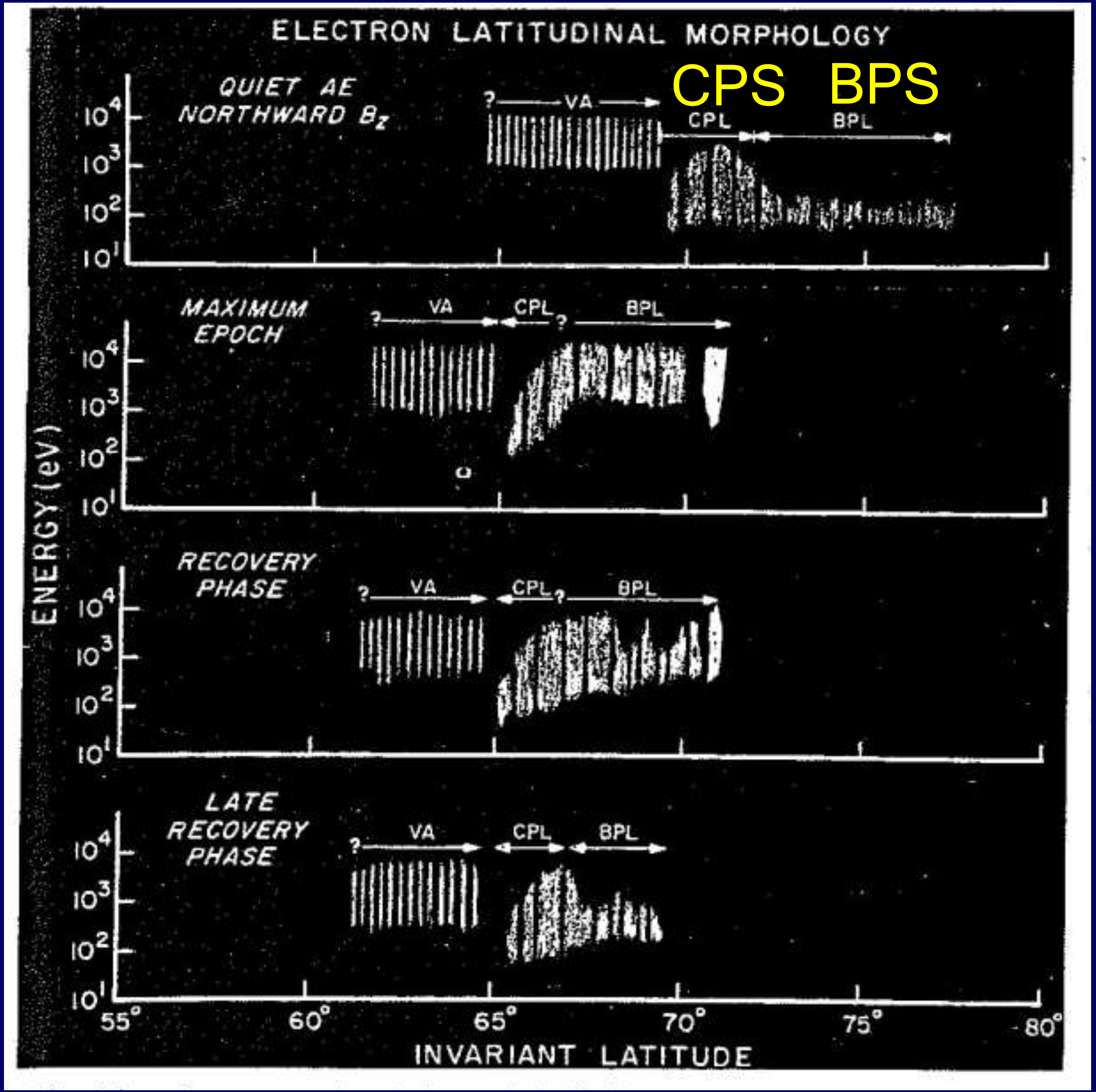


Auroral particles come from the plasma sheet

Various domain in the magnetosphere



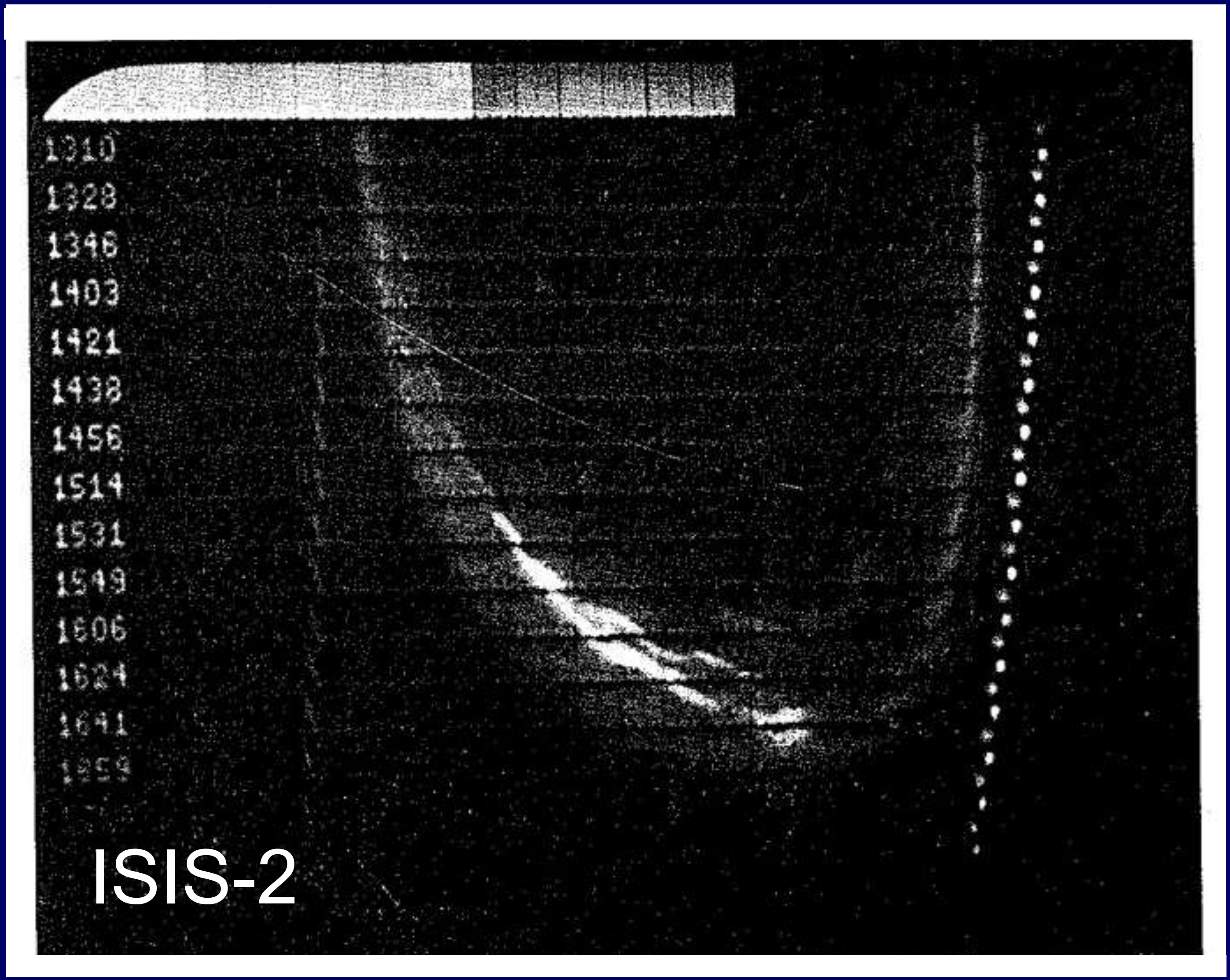
Precipitating electron spectra



ISIS-2

Winningham et al. [1975]

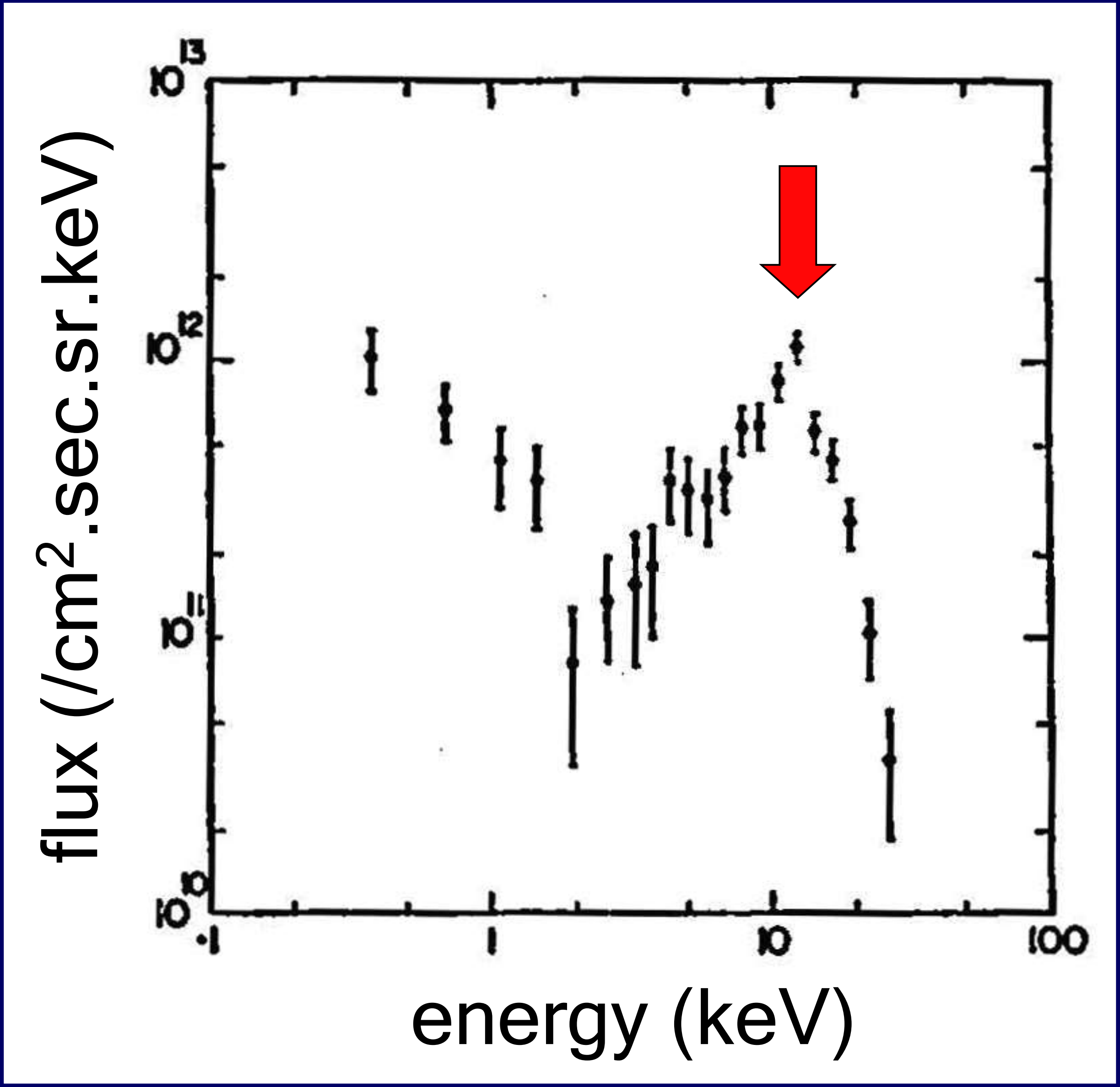
Discrete Aurora & Diffuse Aurora



Discrete aurora : BPS type electron precipitation

Diffuse aurora : CPS type electron precipitation

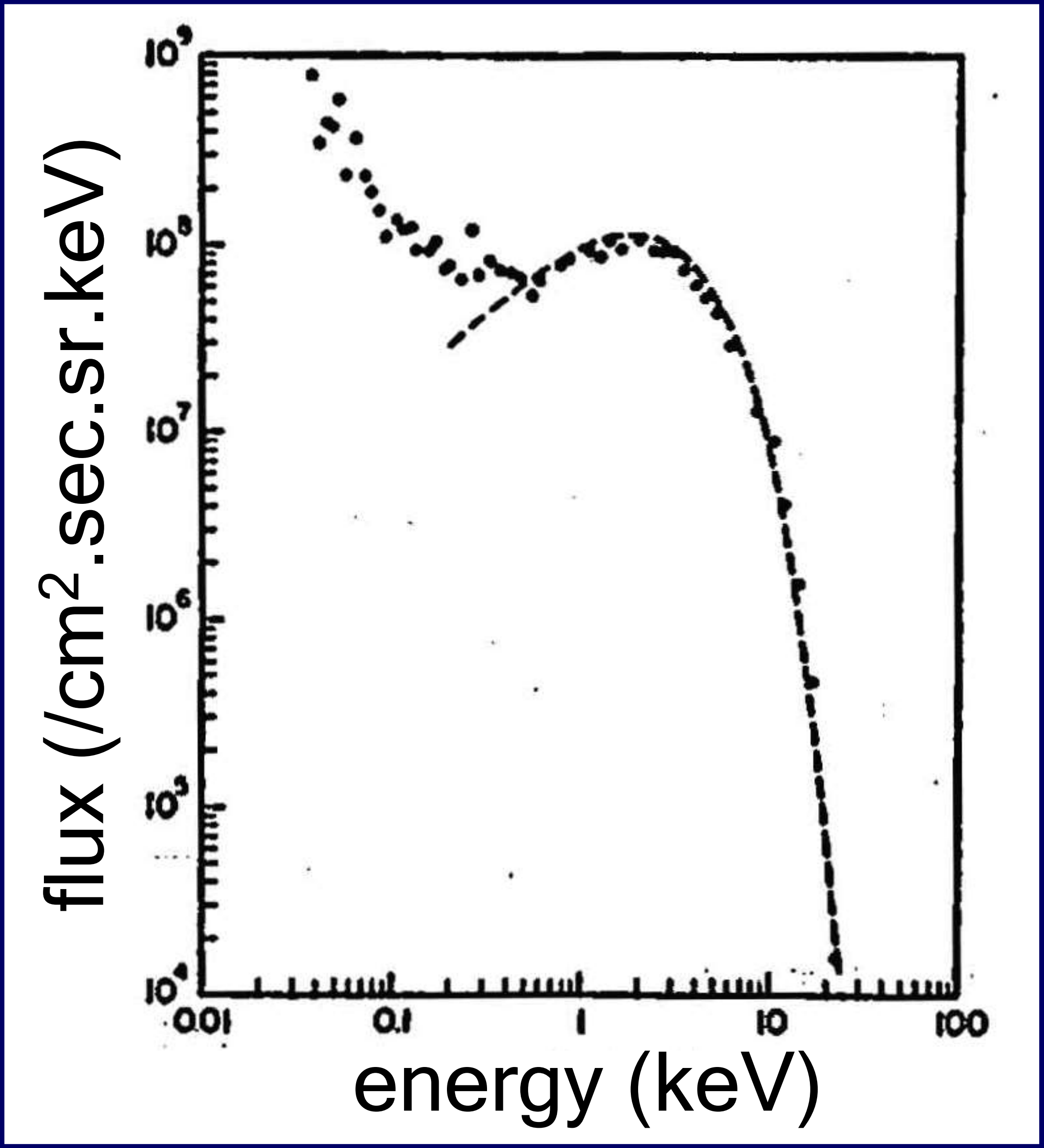
Energy spectrum of auroral electrons



Rocket observation for Discrete Aurora

accelerated mono-energetic peak

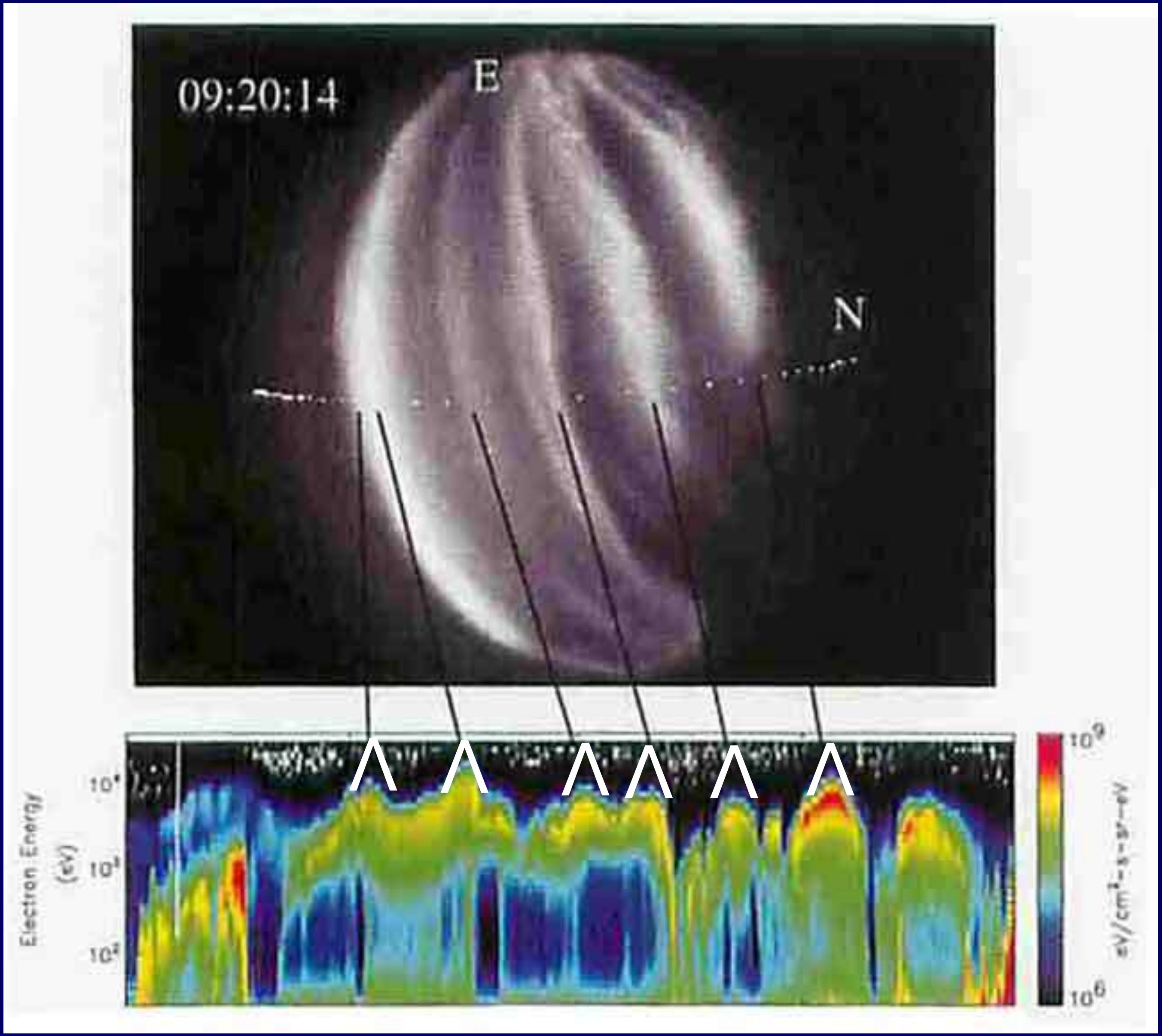
Energy spectrum of auroral electrons



Rocket observation for Diffuse Aurora

Maxwell distribution

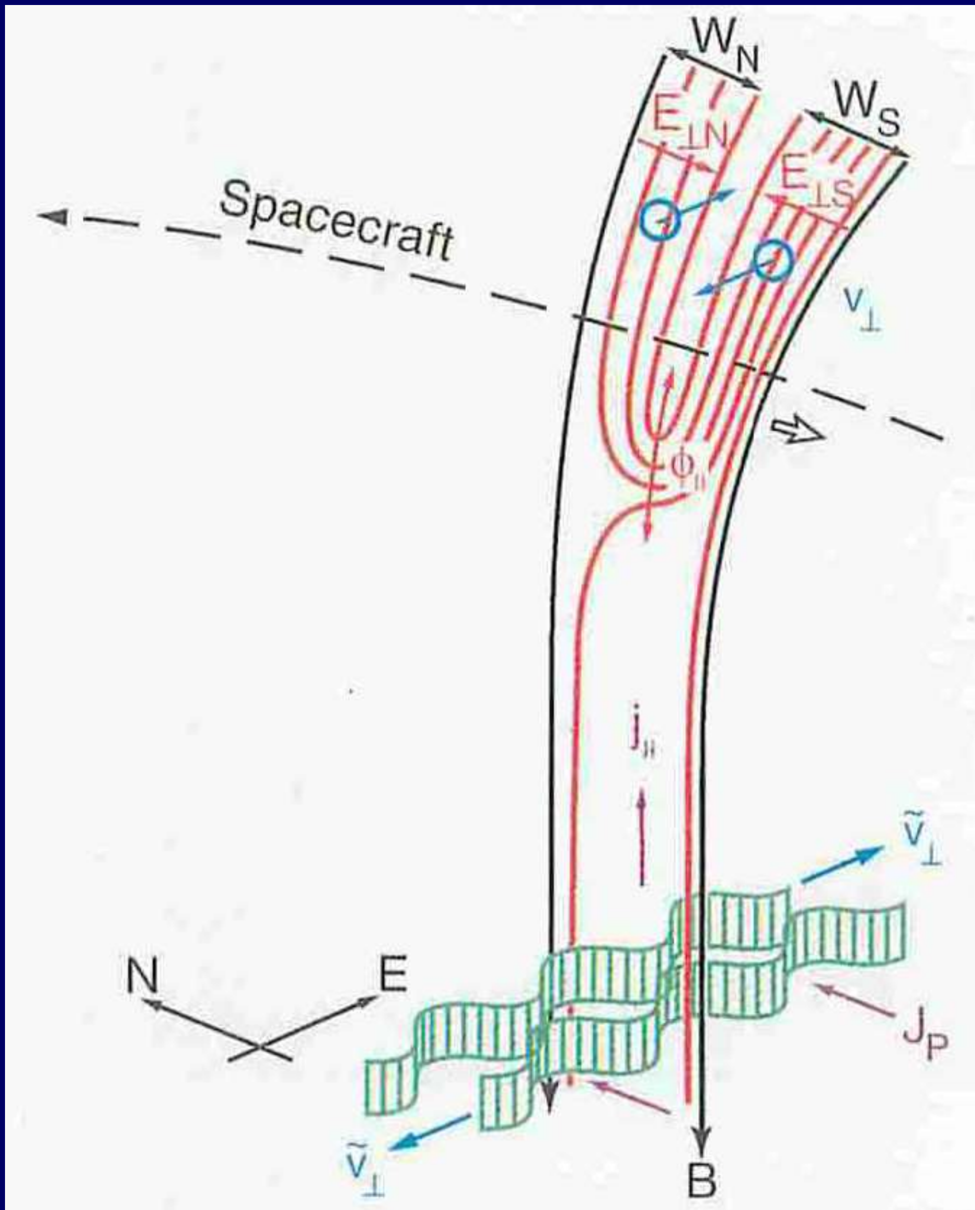
Energy spectrum of auroral electrons



FAST satellite

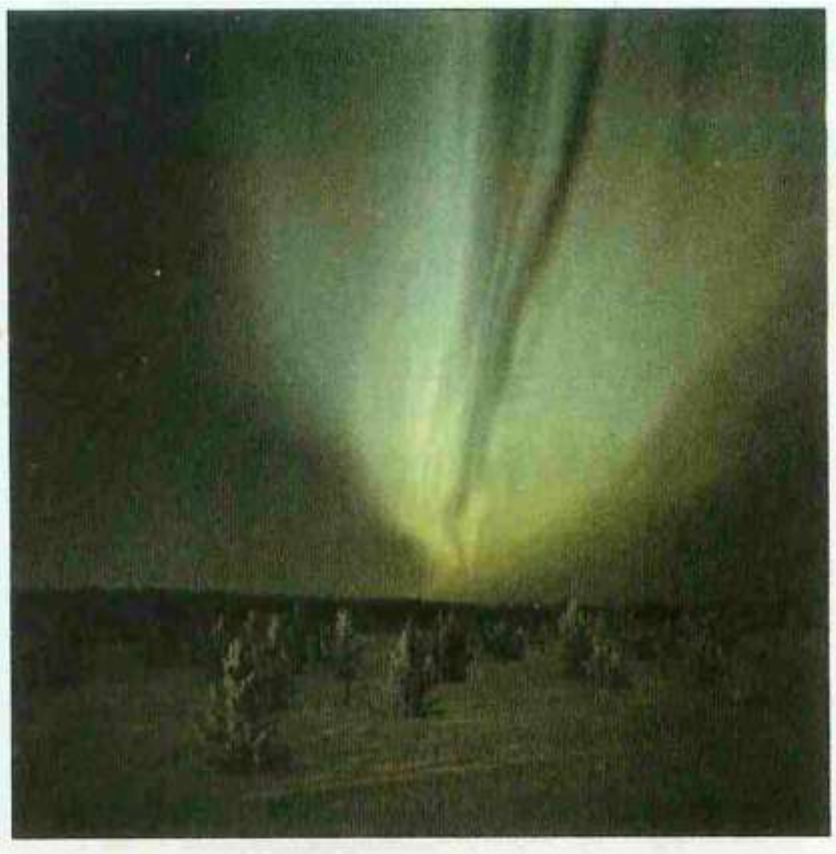
“inverted-V” spectra

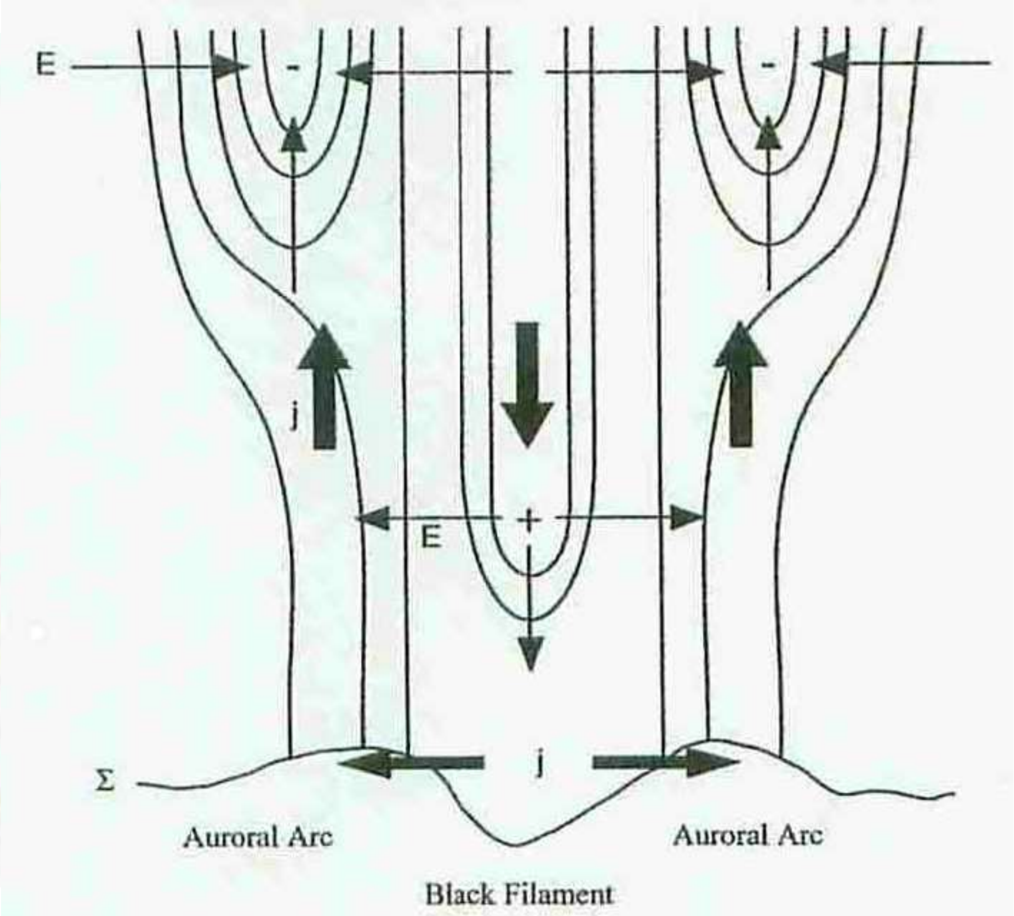
Upward field-aligned Electric field



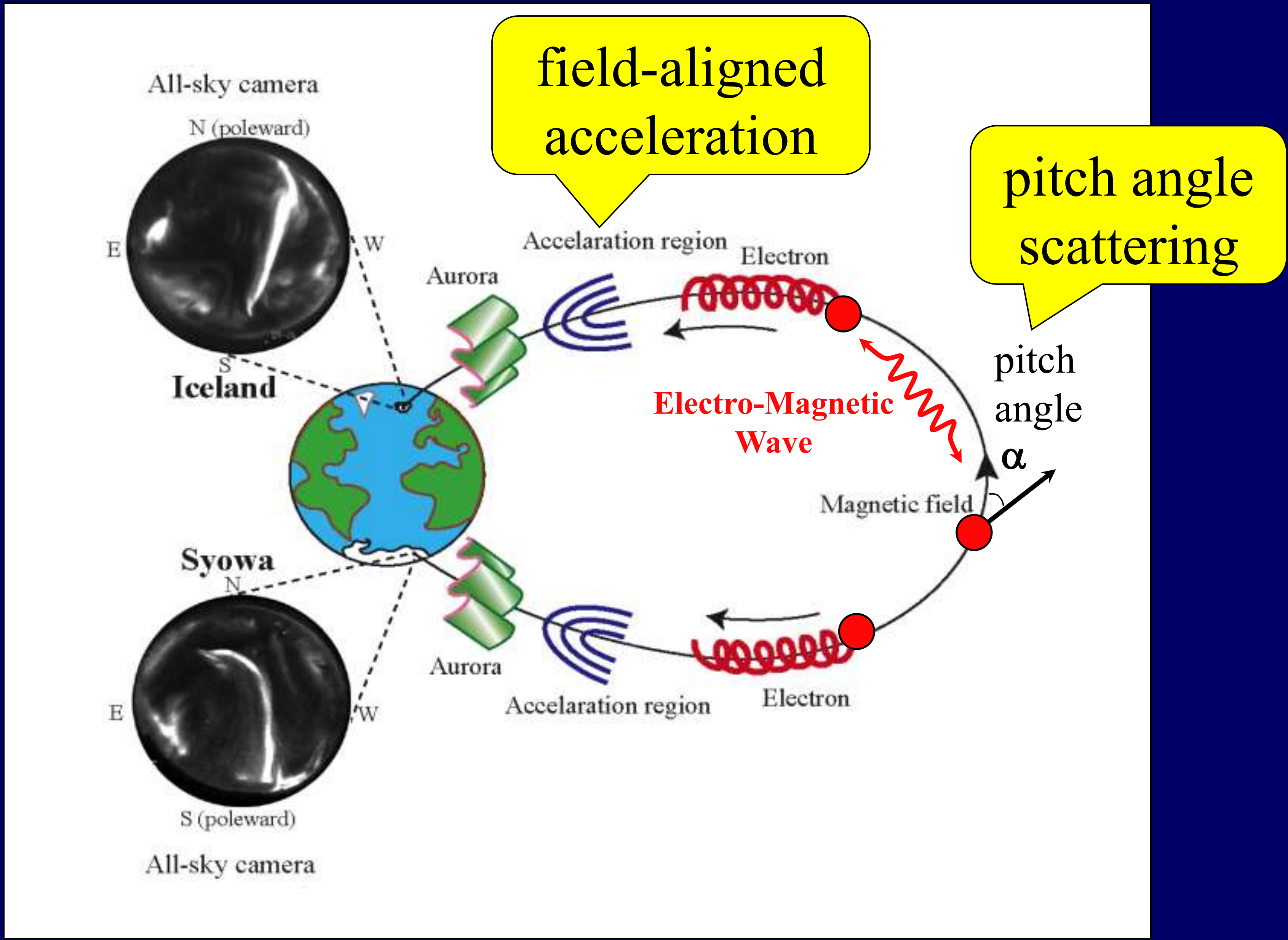
at 1000～10000 km to accelerate the auroral electrons

Current closure around the Auroral arc

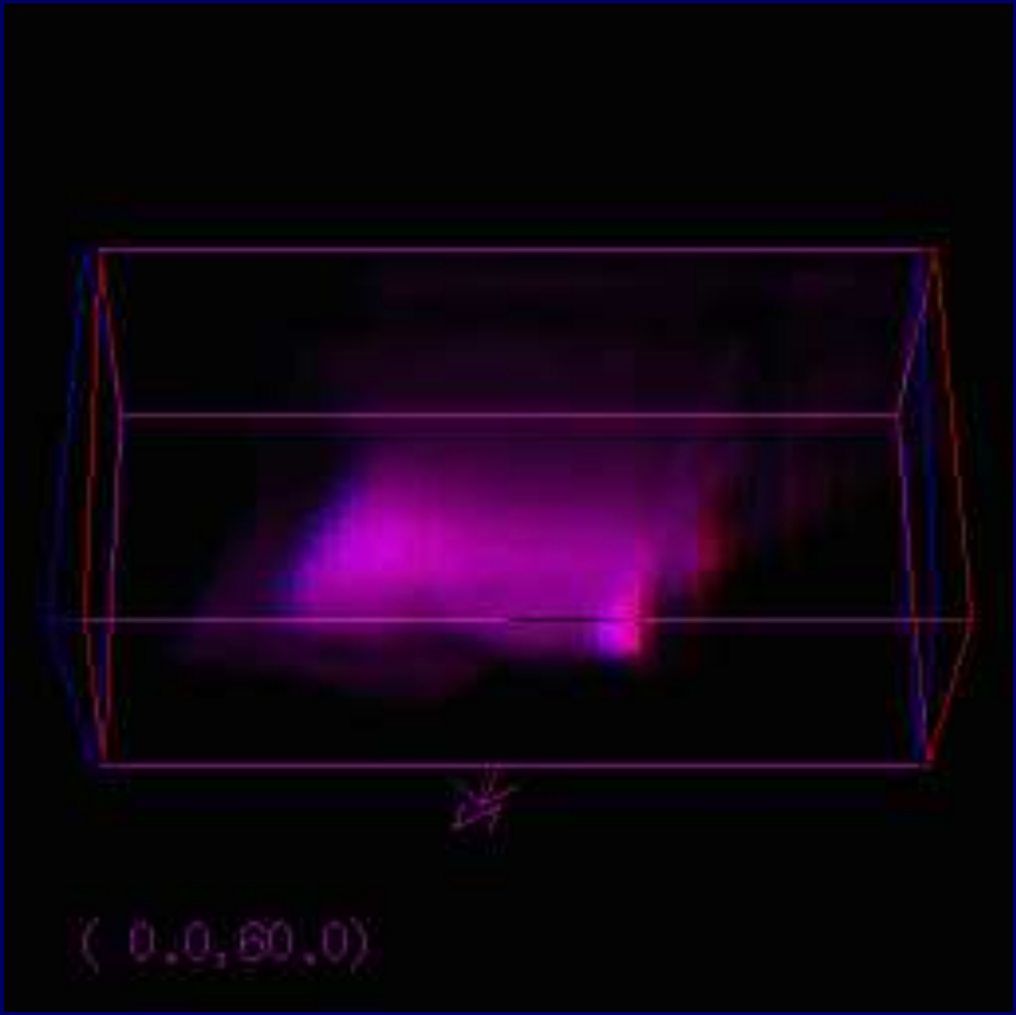




Auroral particle precipitation mechanism

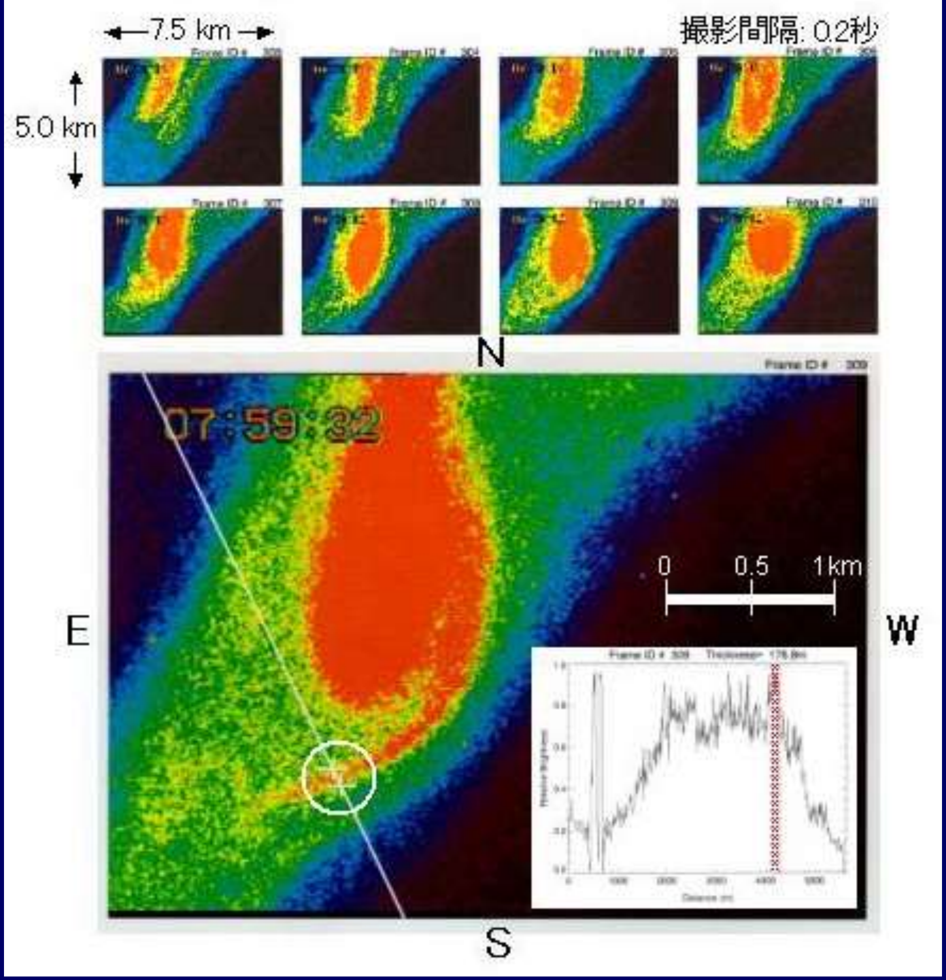


3D structure using Auroral tomography



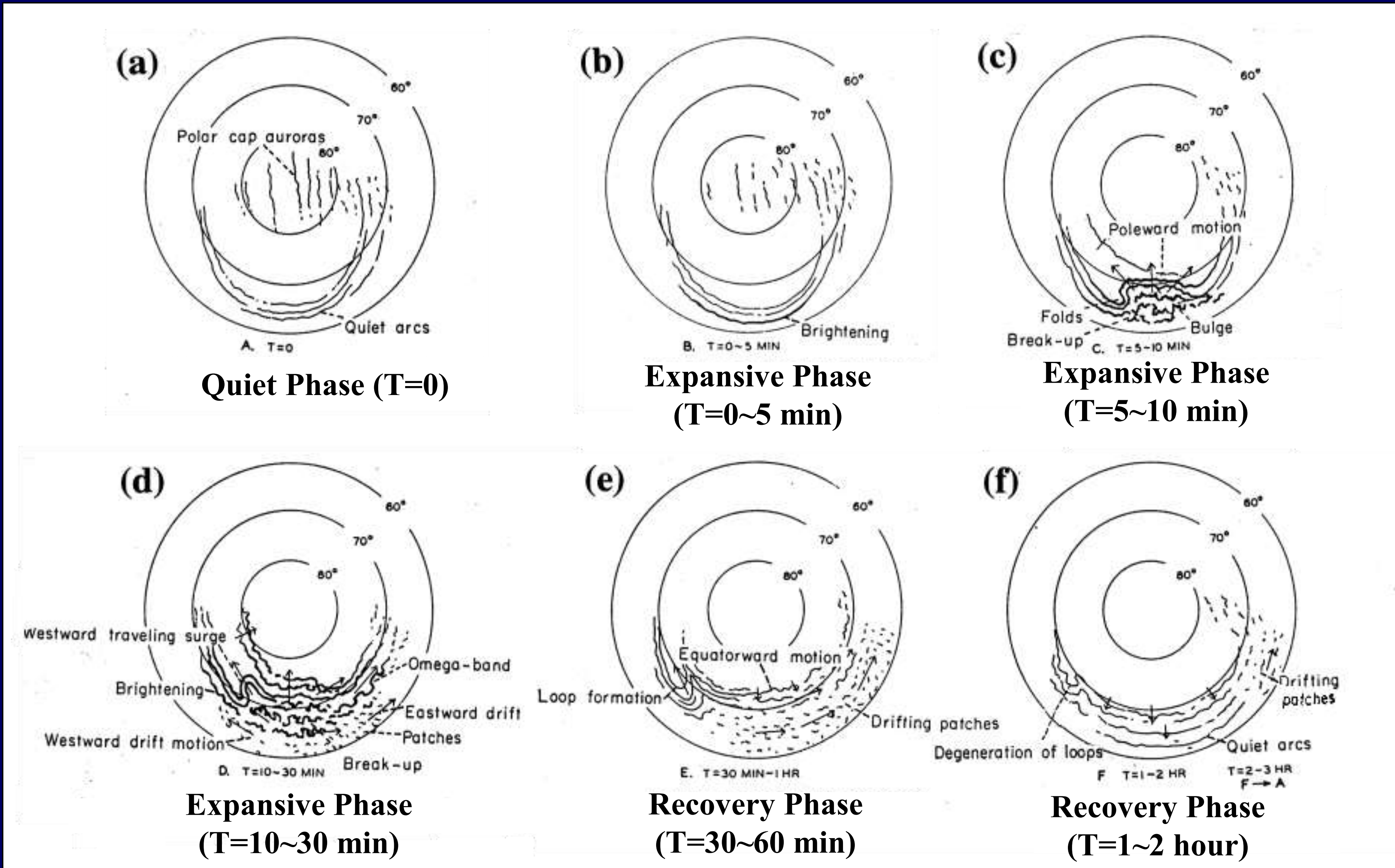
557.7nm

Auroral small structure by narrow FOV camera

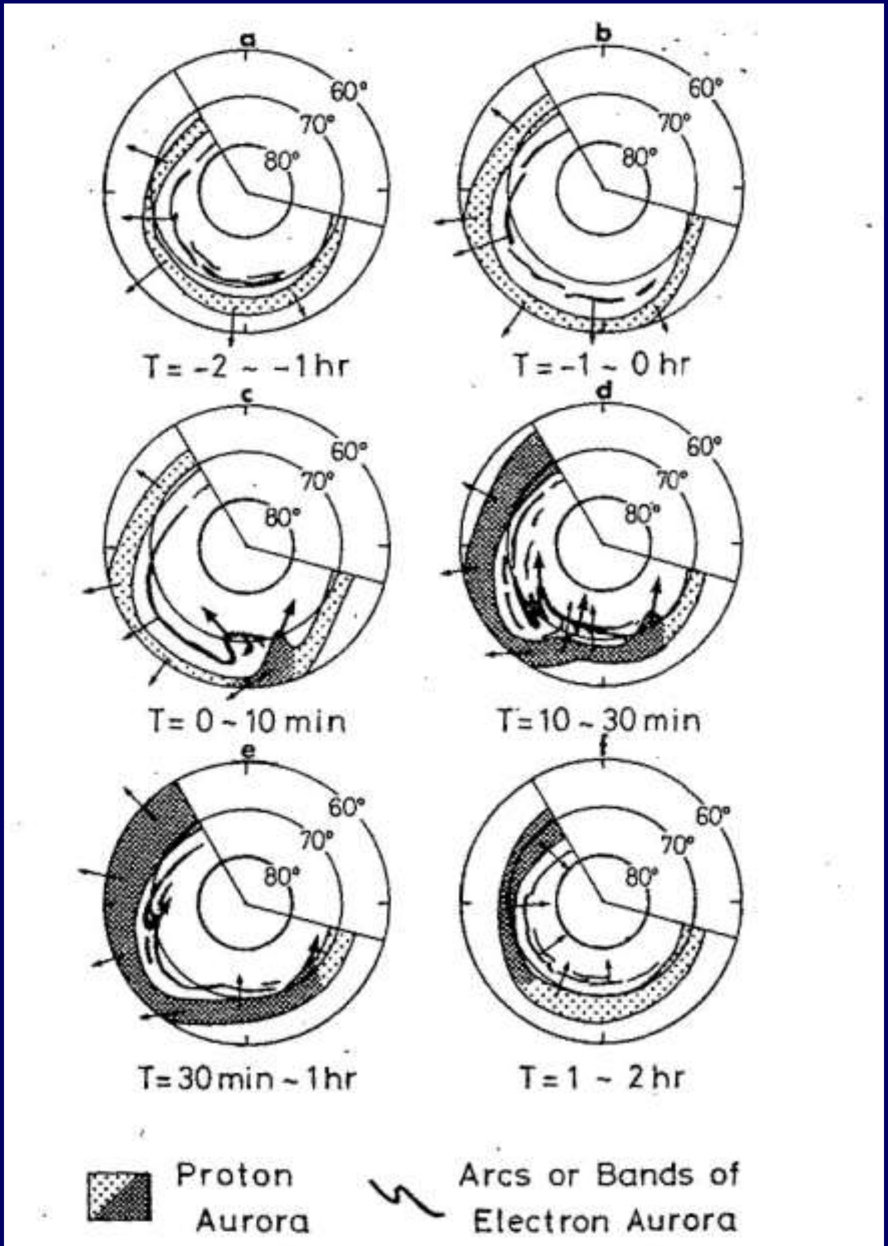


Auroral Substorm

Classical Morphology by *Akasofu* (1964)



Modification to the Akasofu Classical Morphology

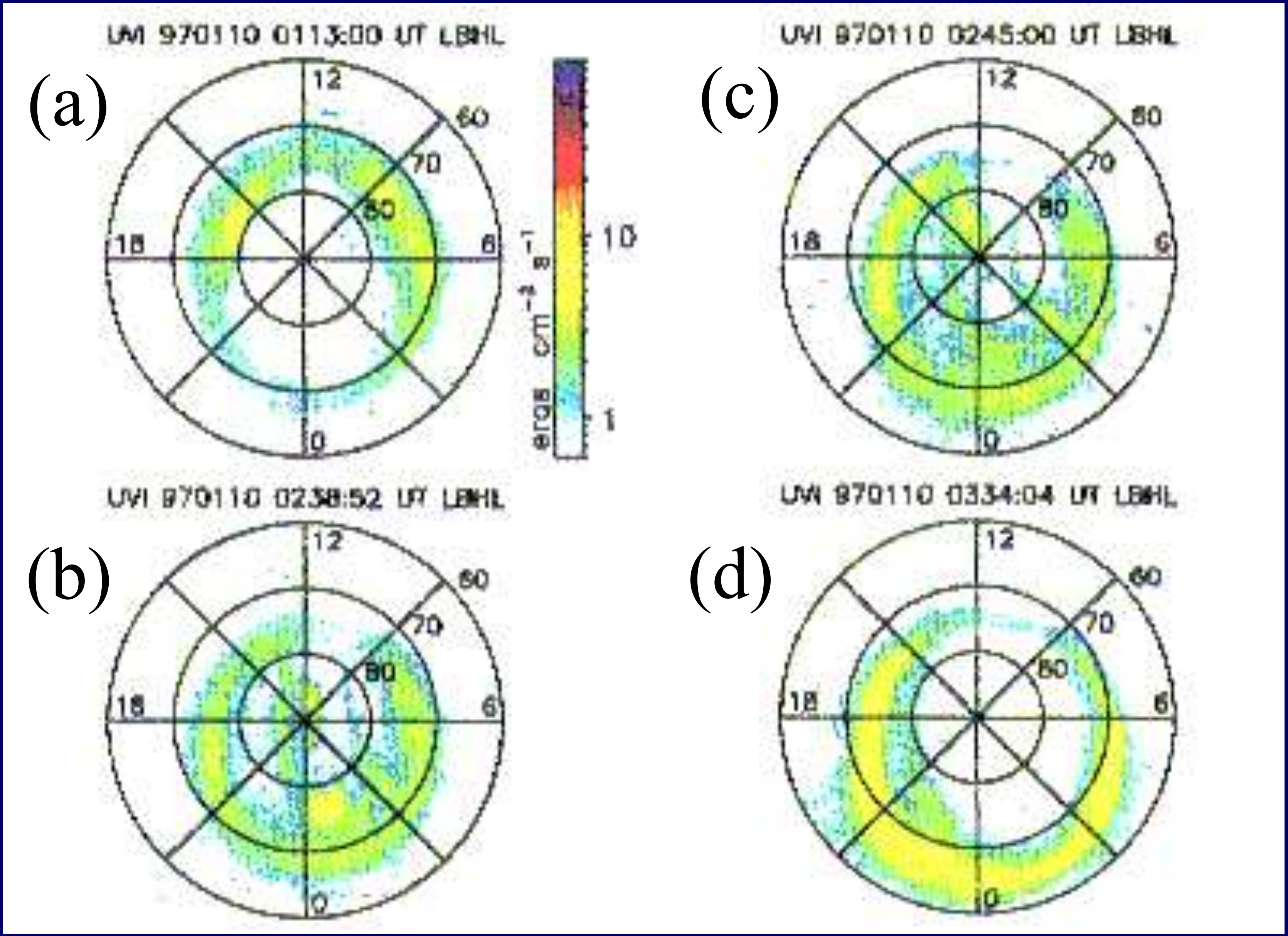


Proton Auroral Substorm

Fukunishi (1975)

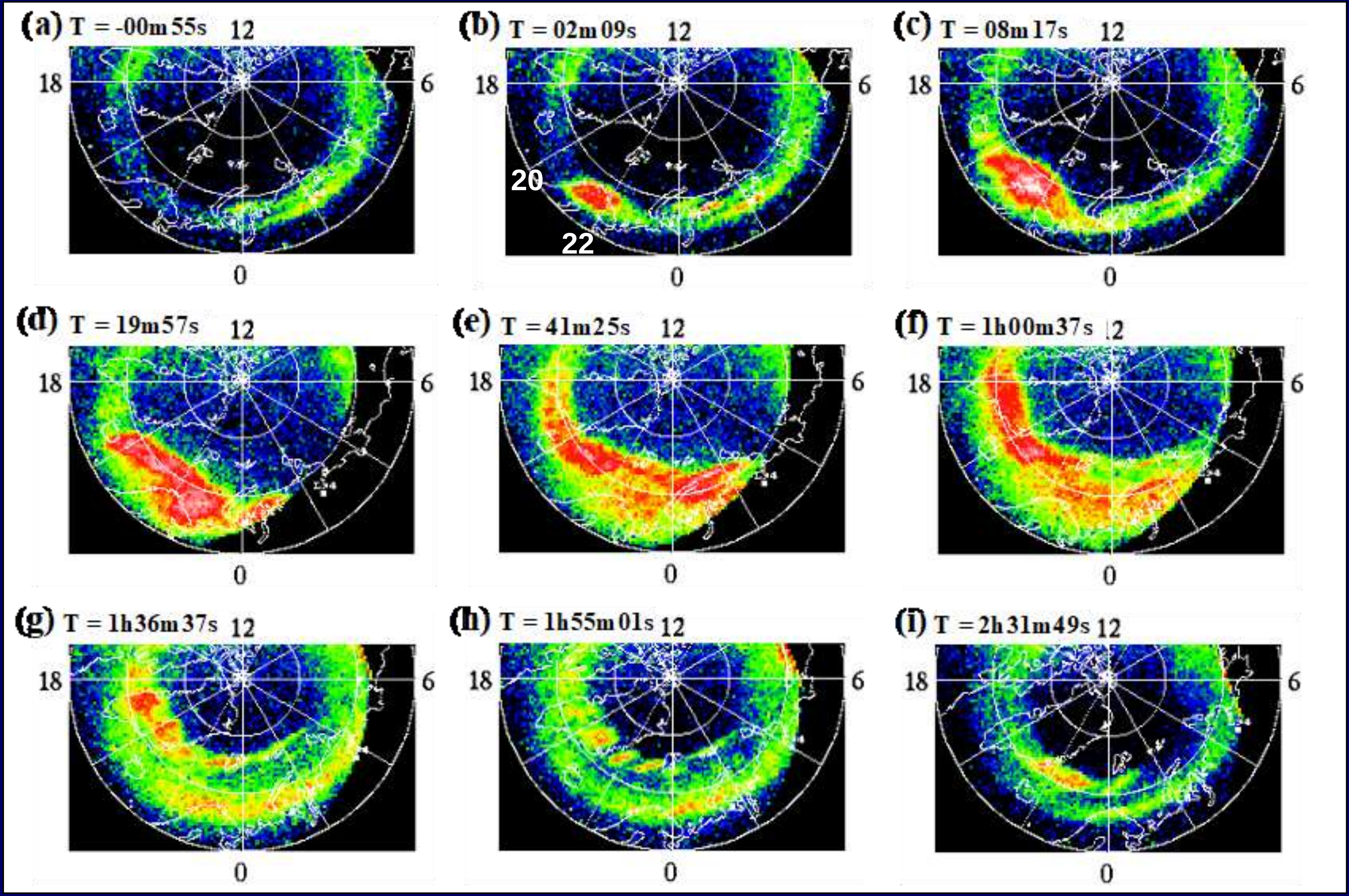
Modification to the Akasofu Classical Morphology

Discovery of the Growth phase



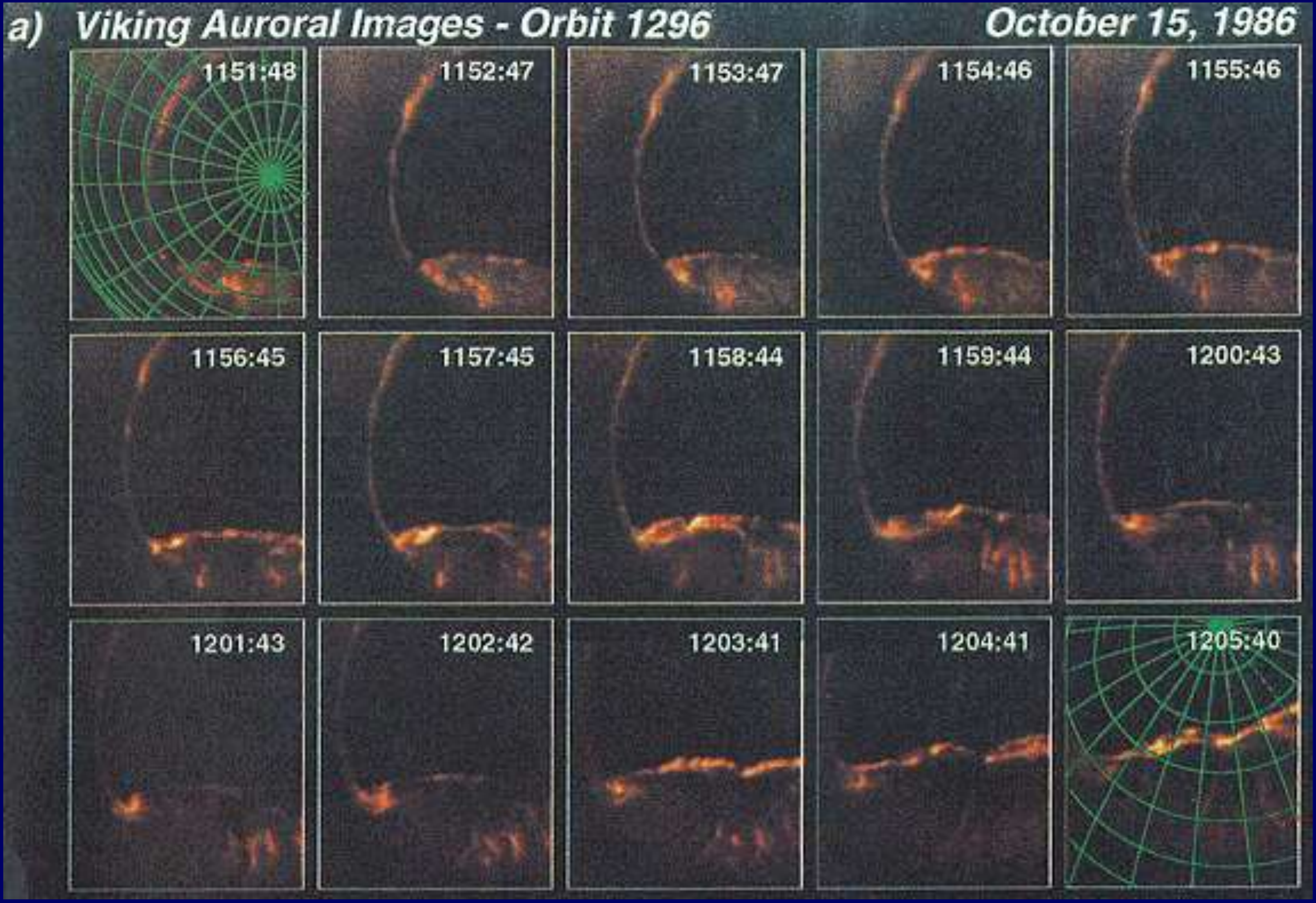
Modification to the Akasofu Classical Morphology

Localization & pre-midnight preference of Onset



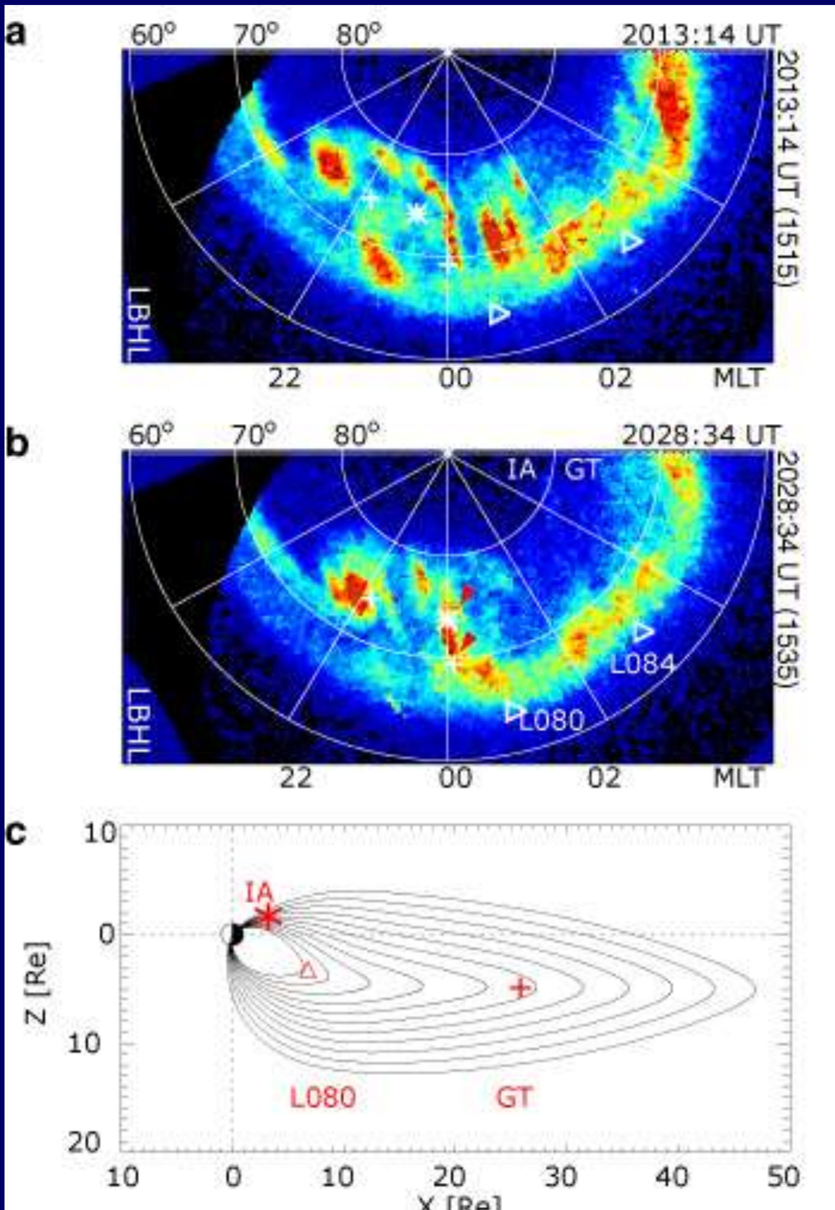
Modification to the Akasofu Classical Morphology

North-South aligned (N-S) aurora



Henderson et al. (1998)

N-S Aurora or Auroral Streamer



projection of the fast earthward flow ?

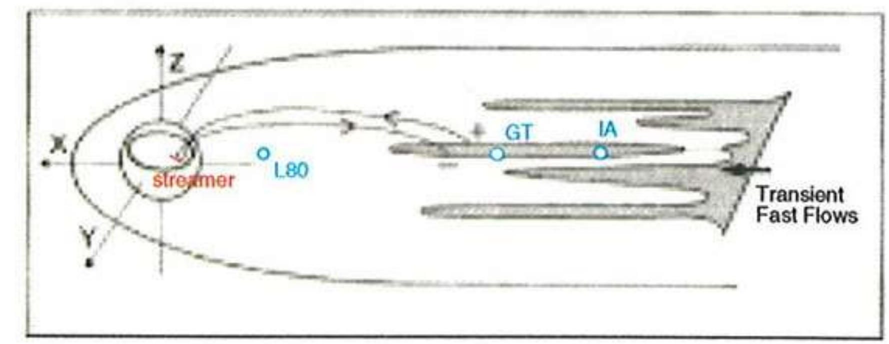
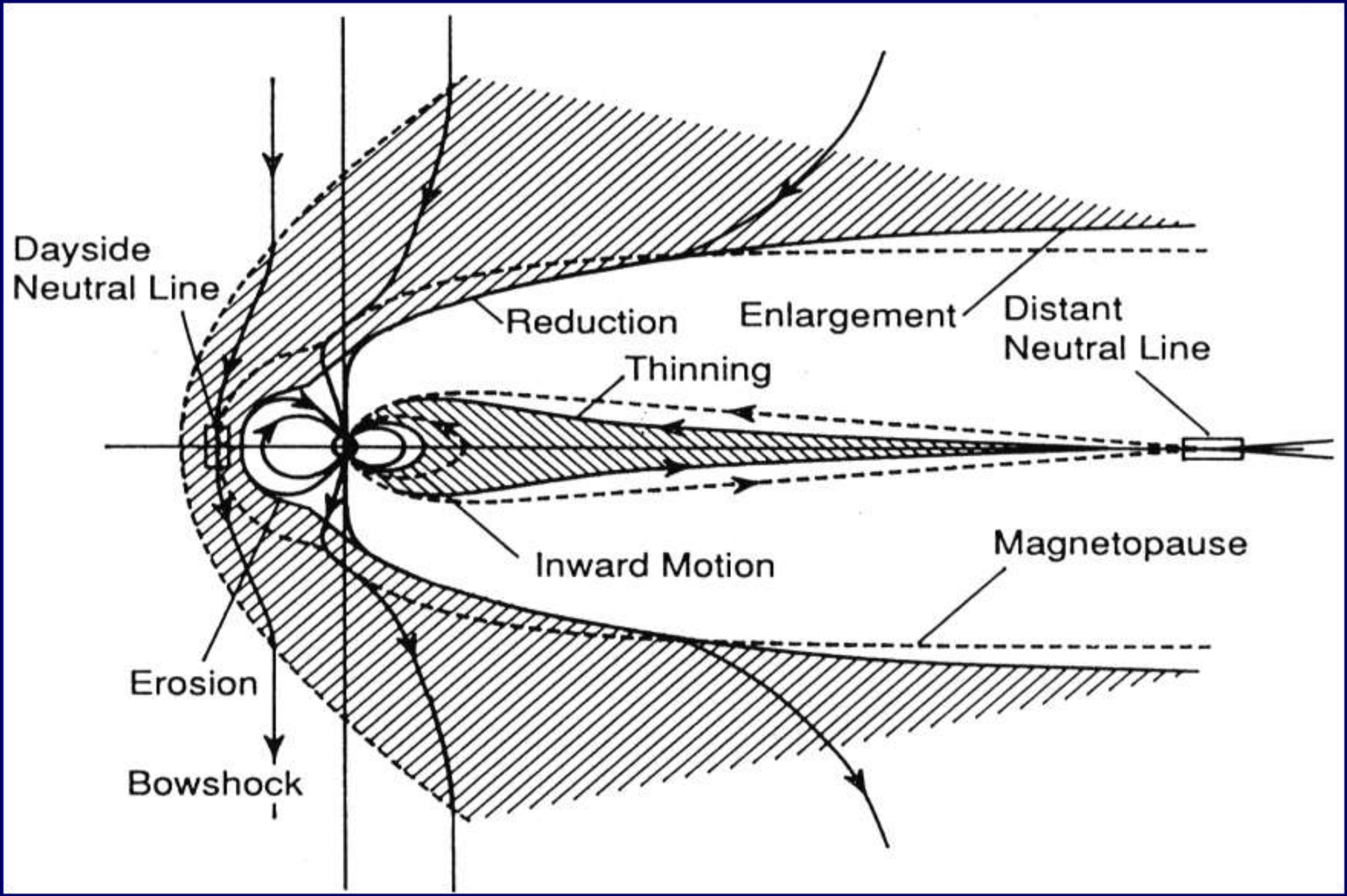


Figure 3. Schematic picture of transient plasma jets (updated from *Sergeev et al.*, [1996a]). Equatorial mapping of basic spacecraft is also shown. Strong plasma jet is just passing in the equatorial plane past the equatorial footpoint of Interball-Auroral and Geotail spacecraft and is approaching the inner magnetosphere, as occurred at ~2025 UT on December 10, 1996. Precipitation of electrons accelerated in the jet-associated upward field-aligned current forms the auroral streamer seen on the Polar UVI images.

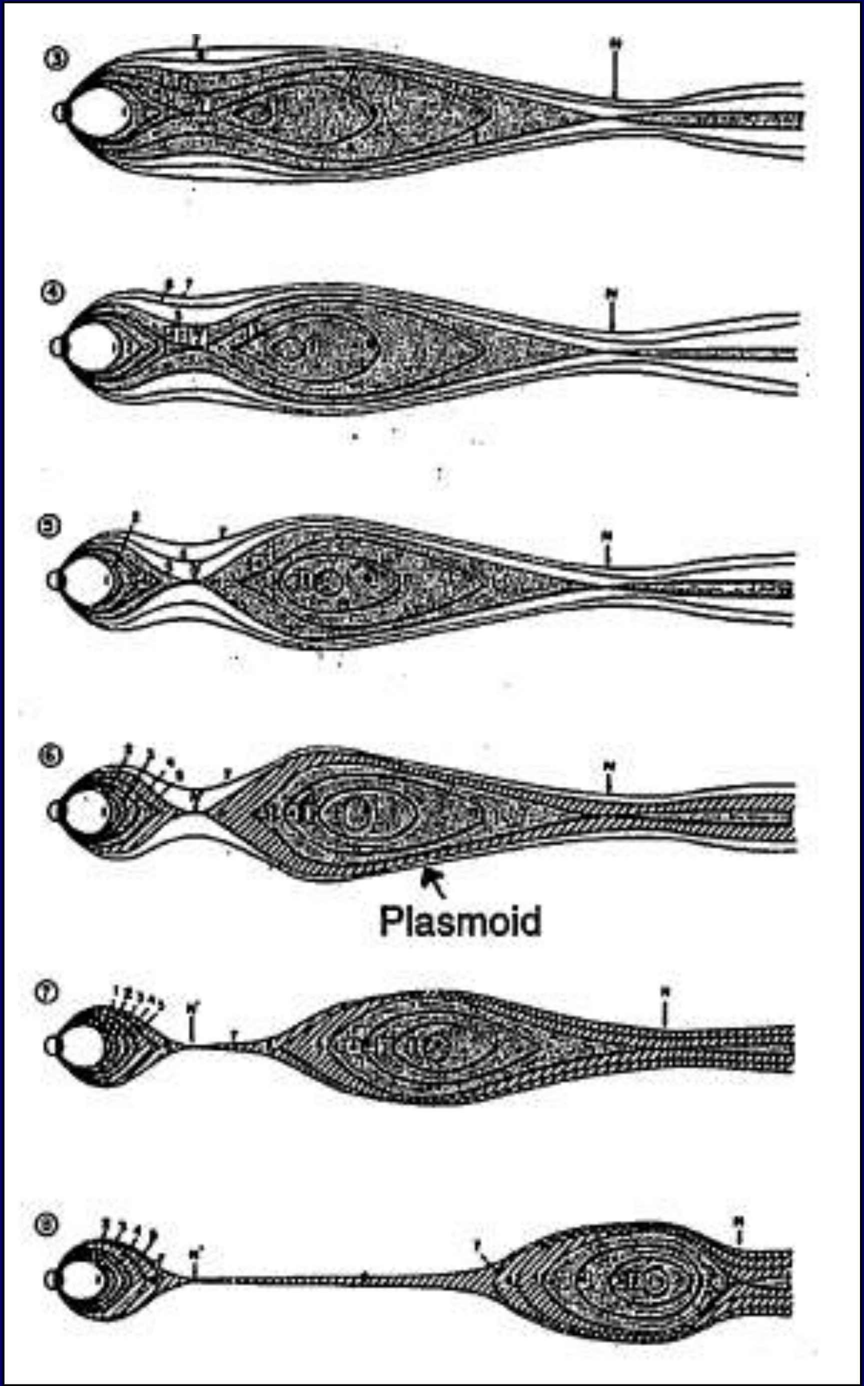
Sergeev et al. (2000)

Growth phase in the magnetosphere



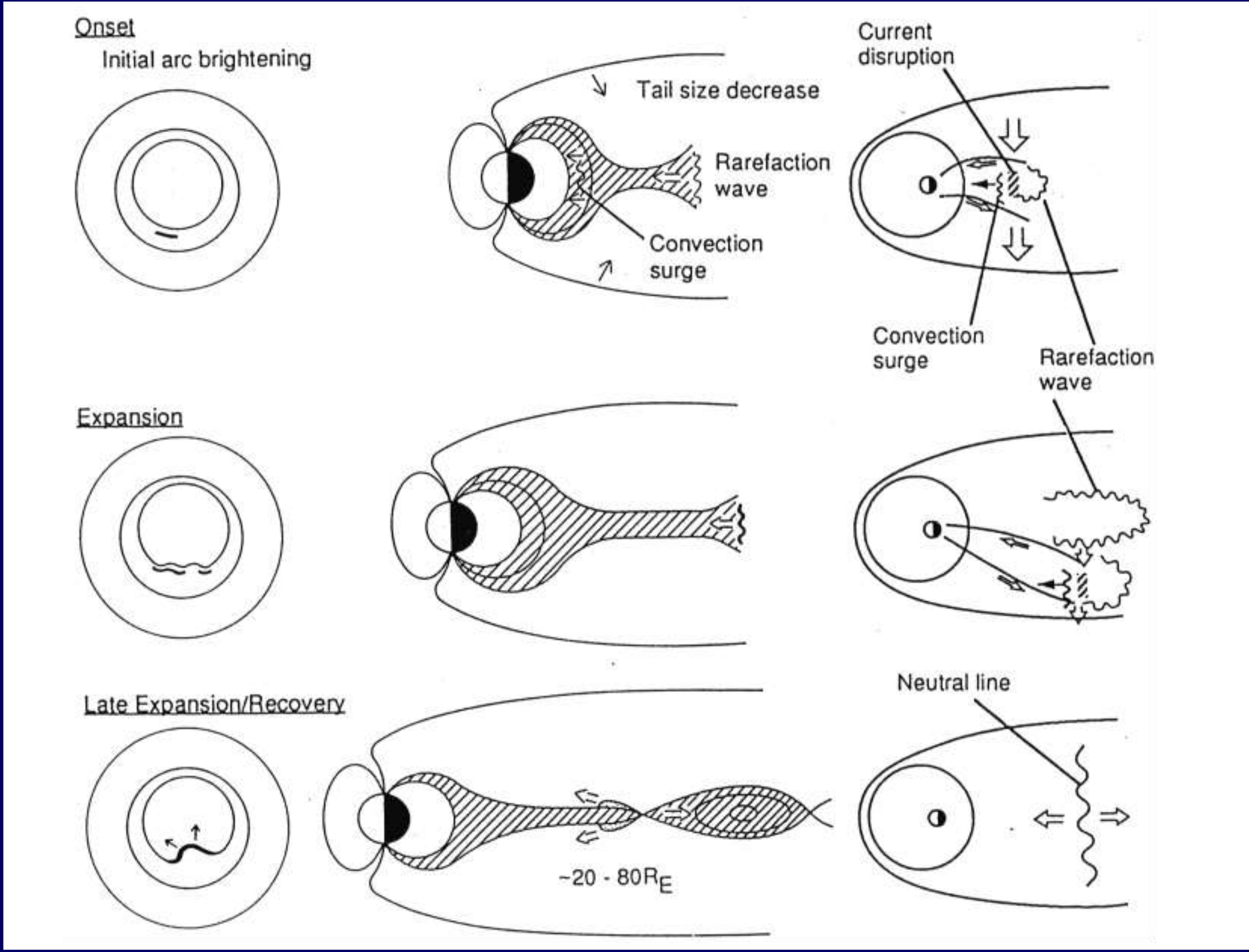
Substorm in the magnetosphere

NENL (Near Earth Neutral Line) model



Current Disruption model

Lui (1991)



Other issues : Ionospheric effect on aurora

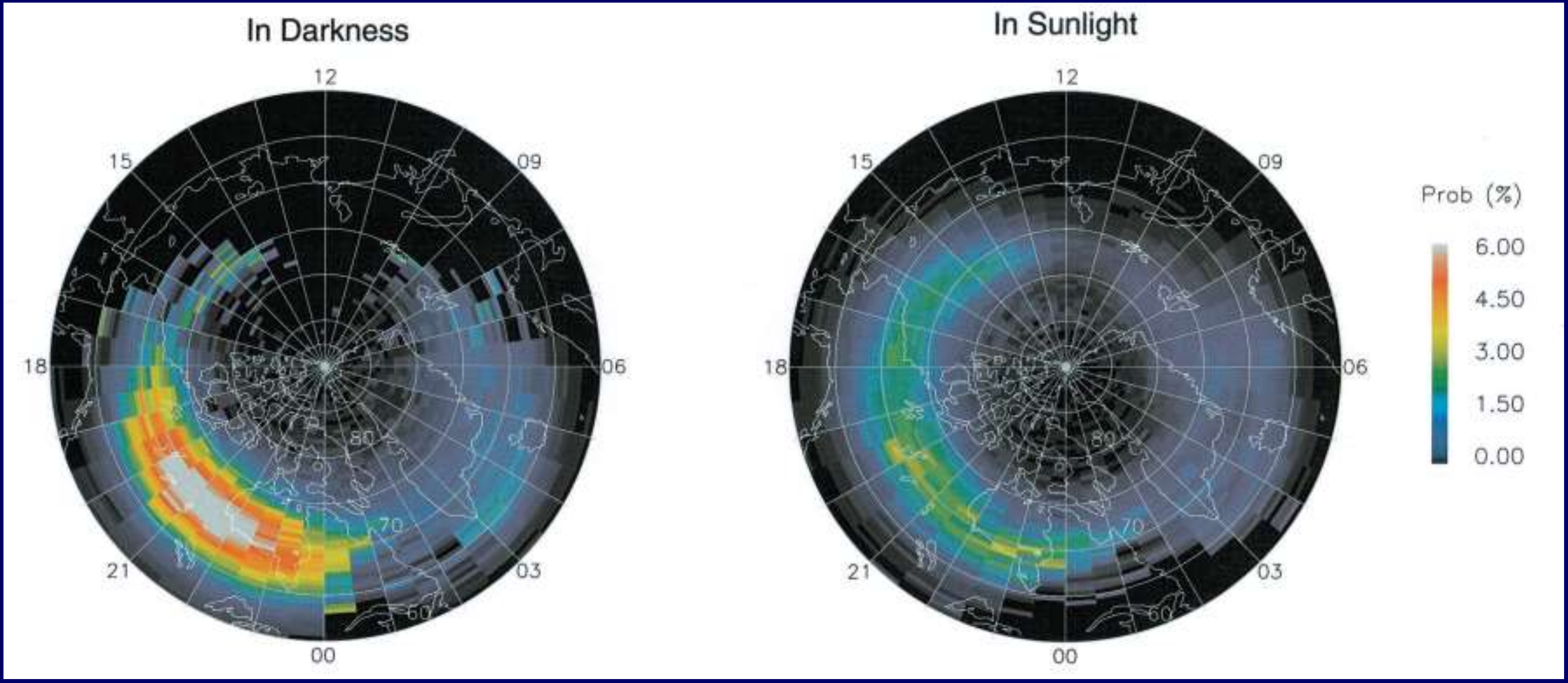
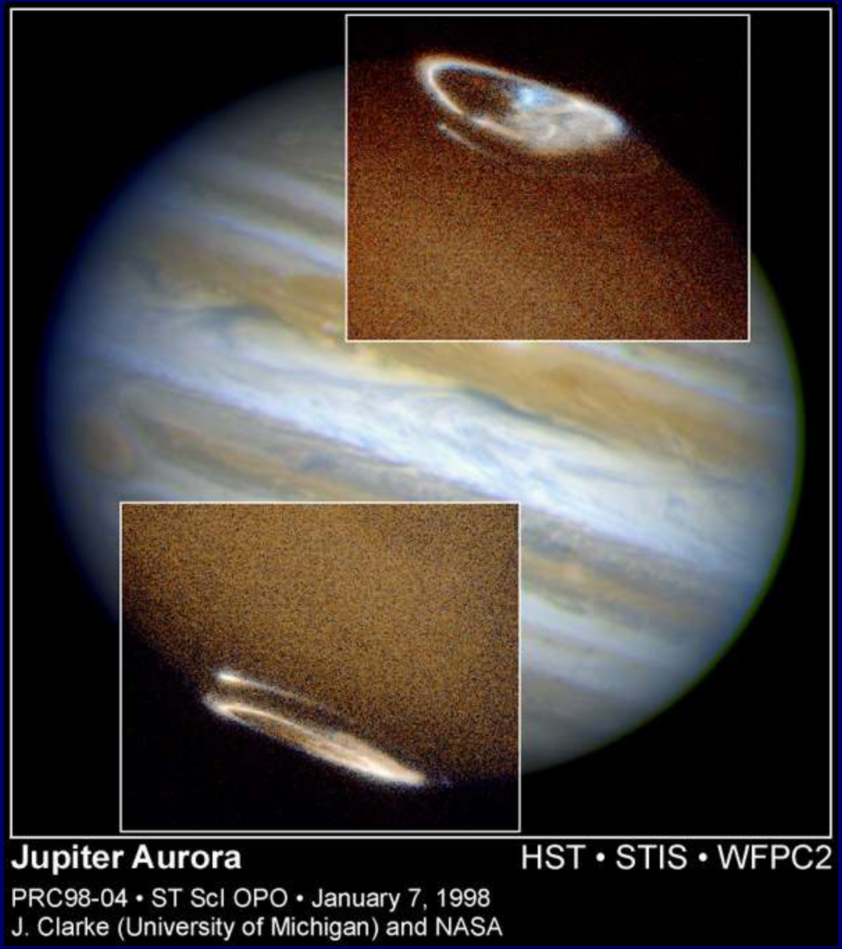
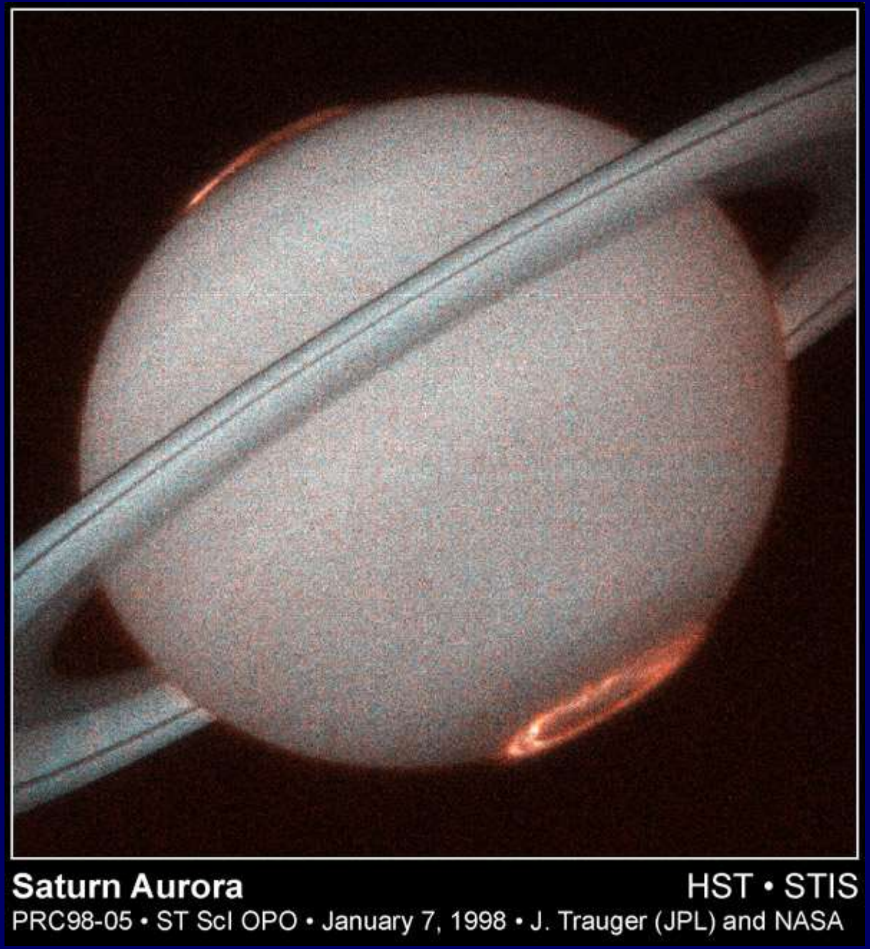


Plate 1. Intense discrete auroras occur much more frequently in darkness than in sunlight. This effect is attributed to the increase in ionospheric conductivity caused by sunlight. The above plots show the probability of observing intense discrete auroras (.5 ergs cm-2 s-1) in corrected magnetic coordinates, with the continental outlines shown at 0600 UT.

Newelll (2001)

Auroras on the other planets





Jupiter

Saturn

Conditions for the planetary aurora

The planet should have

- ✧ Atmosphere
- ✧ Source of auroral particles
- ✧ Own magnetic field

There are still many un-resolved problems for Aurora

- ✧ Mechanism of the Pulsating Aurora
- ✧ Exact correspondence between the Auroral and Magnetospheric substorms
- ✧ Source mechanism of the field-aligned Electric field
- ✧ Source mechanism of the various auroral motion (Curl, Spiral, Spliting, ...)
- ✧ Acceleration mechanism of auroral protons