Prediction of AL index
on the basis of the solar wind

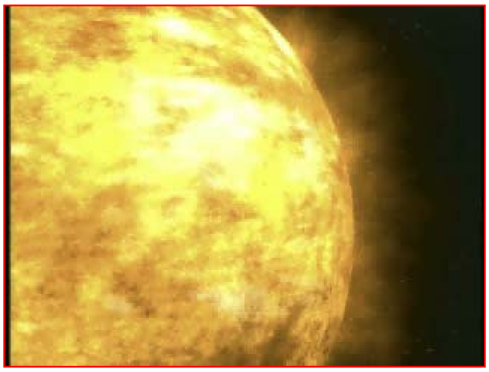
Kap Soo Oh (Chungnam National University)
Xinlin Li (LASP)
M. Temerin (SSL)

1. Introduction

- Geomagnetic Indices
  - Kp –
    - Derived from mid-latitude magnetometers (~13)
    - Logarithmic scaling
    - 3-hour time resolution
    - Σ Kp (daily value) often used
  - Ap –
    - ap ; linear scaling of Kp (3-hour time resolution)
    - Daily index by averaging 8 ap values
    - Same (mid-latitude) K stations used
  - Dst –
    - Derived from 4 low-latitude observatories
    - Quiet-day corrected H-components used
    - Hourly time resolution

- Geomagnetic Indices (conti.)
  - ASY/SYM – Family
    - ASY – longitudinally asymmetric (4 groups)
    - SYM – longitudinally symmetric (2 groups)
    - mid-latitude (1-minute time resolution)
    - H: dipole direction, D: east-west direction
    - (e.g. SYM-H : similar to Dst)
  - AE – Family
    - Derived from (sub)auroral stations (~12)
    - Upper/lower envelope of ΔH superposition
    - 1-minute time resolution

Coronal Mass Ejection



- Motivation

Temerin & Li (2002) ; The magnetosphere is highly predictable and the chaotic behavior within the magnetosphere has little influence on the large-scale currents that determine *Dst* (1 hour resolution data).

Does the magnetosphere still have an organized response on the small-scale current and in a shorter time scale related with auroral electrojet ?

2. Measurement and Definition of Electrojet Indices

- Davis & Sugiura (1966) introduced the auroral electroject indices to characterize the currents in auroral latitude region.

- geomagnetism, aeronomy and solar-terrestrial physics for monitoring geomagnetic activity and space weather

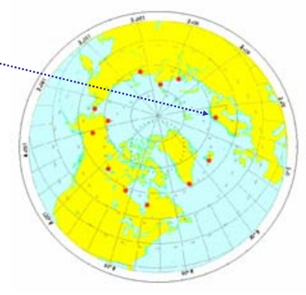
- 1957 – 1964 ; hourly values (GIUA)
  09/1964 - 06/1968 ; 2.5 minute values (GSFC)
  1966 – 1974 ; 2.5 minute values (WDC-A, Boulder, Colorado)
  1975-04/1977 ; 1 minute values (WDC-A, Boulder, Colorado)
  1978 – present ; 1 minute values (WDC-C2, Kyoto, Japan)

- one minute readings of the northward magnetic field component

- 12 auroral zone observatories
  (60° - 72° ; magnetic latitude, 15° – 50° ; magnetic longitudinal spacing)

List of *AE*(12) Stations.

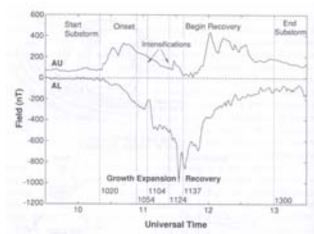
	IAGA	Geographic Coord		Geomagnetic Coord	
Observatory	Code	Lat.(°N)	Long.(°E)	Lat.(°N)	Long.(°E)
Abisko	ABK	68.36	18.82	66.04	115.08
Dixon Island	DIK	73.55	80.57	63.02	161.57
Cape Chelyuskin	CCS	77.72	104.28	66.26	176.46
Tixie Bay	TIK	71.58	129.00	60.44	191.41
Cape Wellen	CWE	66.17	190.17	61.79	237.10
Barrow	BRW	71.30	203.25	68.54	241.15
College	CMO	64.87	212.17	64.63	256.52
Yellowknife	YKC	62.40	245.60	69.00	292.80
Fort Churchill	FCC	58.80	265.90	68.70	322.77
Poste-de-la-Baleine	PBQ	55.27	282.22	66.58	347.36
Narsarsuaq (Narssarssuaq)	NAQ	61.20	314.16	71.21	36.79
Leirvogur	LRV	64.18	338.30	70.22	71.04



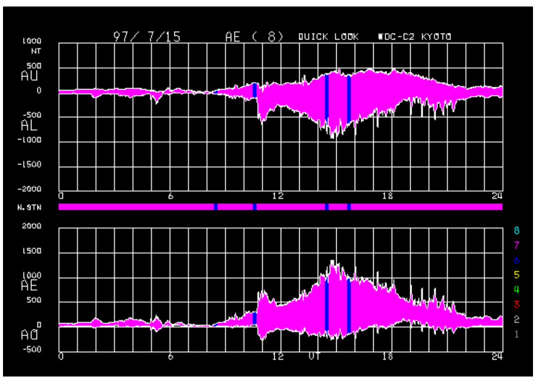
$$AU(t) = \max\{H(t) - H_o\}_{i=1,12}$$
$$AL(t) = \min\{H(t) - H_o\}_{i=1,12}$$
$$AE(t) = AU(t) - AL(t)$$
$$AO(t) = [AU(t) + AL(t)] / 2$$

Ho **; average over all the readings on the five international quietest days in each month**
AU **; maximum eastward electroject current**
AL **; maximum westward electroject current**
AE **; overall activity of the electrojets**
AO **; measure of the equivalent zonal current**

Sanpshot of ionospheric convection during growth phase ; DP-2 system (disturbance polar of the second type) Convection electrojets by Hall current [Clauer and Kamide,1985]



March 22, 1979 substorm event [McPherron and Manka, 1985]



Courtesy T. Kamei

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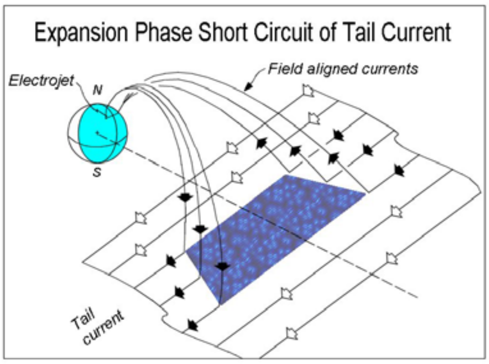
Uncertainties

1) longitudinal gaps in the distribution of the twelve observatories
2) small latitudinal range
3) effects of strong local field-aligned wedge currents

The Substorm Current Wedge



McPherron et al.

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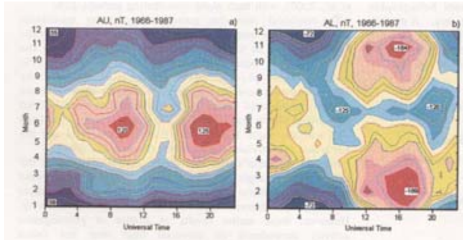
3. Variations of Electrojet Indices

A. universal time (Lyatsky et al. 2001)
B. season (Ahn et al. 2000)



Seasonal and diurnal variation in *AU* and *AL* [Lyatsky et al. 2001]

- Ahn et al. 1999
  AU ; mostly from stations located at the dusk sector
  Hall conductance mainly due to ionized particles by solar EUV
  maximum occurs during summer
  AL ; mostly from stations in the post midnight-early morning sector
  Hall conductance mainly by auroral particle precipitation,
  less sensitive to season
  semiannual variation associated with the seasonal modulation of
  the magnetic field due to offset of dipole axis ; Russell - McPherron effect

- Lyatsky et al. 2001
  geomagnetic activity peaks when the night side auroral zones of both
  hemispheres are in darkness at equinoxes
  no conducting path exists in the ionosphere ; unstable to geomagnetic disruptions
  explains both universal time and seasonal dependences of *AL*
  not an alternative to the Russell - McPherron effect, but rather complementary

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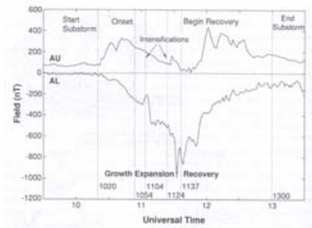
Different dependences of *AU* and *AL* on
1) universal time
2) variation pattern of the year
3) time lag of peak occurrences ;
AU peak is usually several tens of minutes behind *AL* peak.



March 22, 1979 substorm event [McPherron and Manka, 1985]

Different dependences of *AU* and *AL* on
1) universal time
2) variation pattern of the yearly mean
3) time lag of peak occurrences ;
AU peak is usually several tens of minutes behind AL peak.

⇒ *AE* = *AU* - *AL* ; physical meaning ?

AU & *AL* ; separate time series (Ahn et al. 1999, Kamide & Rostoker 2004)

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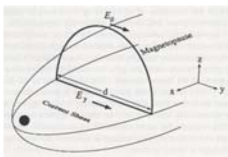
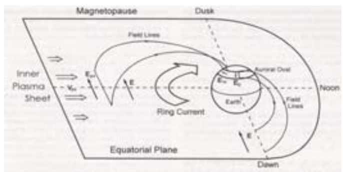
4. Prediction and Forecasting Models

A. Analogue Models

1) Faraday loop model (Klimas et al. 1992, 1994) ; loading –unloading scheme





\+ simple mapping (Weimer, 1993) of cross-tail electric field to *AL*
for data in Bargatze et al. (1985), moderate activity intervals
(2.5 minutes resolution for 140 hours, Nov. 1973 - Dec. 1974)

⇒ Klimas et al. (1994) ; correlation coefficient ~ 0.65

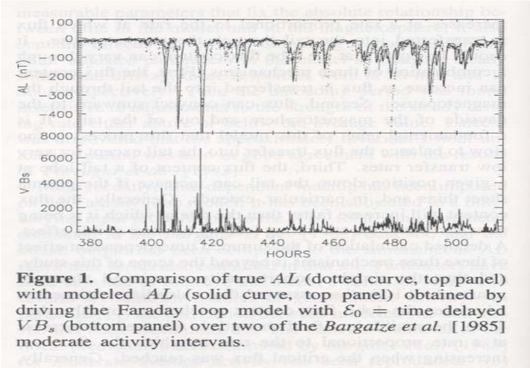


Figure 1. Comparison of true AL (dotted curve, top panel) with modeled AL (solid curve, top panel) obtained by driving the Faraday loop model with $\mathcal{E}_0$ = time delayed VB_s (bottom panel) over two of the *Bargatze et al.* [1985] moderate activity intervals.

2) Directly driven model
(Goertz et al. 1993)

- ionospheric currents are driven by inductively filtered magnetospheric electric fields. ($E_y = -\alpha(\vec{V}_{sw} \times \vec{B}_{sw}) \cdot \hat{y}$)

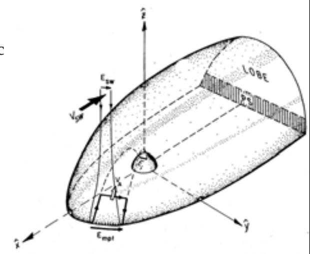


Fig. 3. A sketch of the coupling between the frontside magnetopause and the dayside ionosphere. The reconnection electric field is transmitted toward the ionosphere by an Alfvén wave.

⇒ correlation coefficient of *AE* ~ 0.92 (*AL* ; slightly lower)
(10 minutes resolution for 48 hours, May 18 – 19 , 1979)

B. Input-Output Data Analysis Methods

1) Local-linear prediction filter
(Vassiliadis et al. 1995)

Extension of the linear prediction filter technique to the local-linear prediction technique allows for nonlinear coupling.

data for Nov. 1973 - Dec. 1974 in Bargatze et al. (1985)

⇒ Vassiliadis et al. (1995) ; correlation coefficient
~ 0.79 ; 2.5 minutes resolution for 40 hours
~ 0.87 ; 25 minutes resolution for 40 hours

2) Neural net forecasting

$$O_t = F\,(I_{t-1}, I_{t-2}, \ldots, I_{t-l}, O_{t-1}, O_{t-2}, \ldots, O_{t-l})$$

F ; active function, locally and globally nonlinear

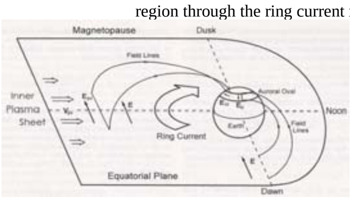
- data for Nov. 1973 - Dec. 1974 in Bargatze et al. (1985)

Hernandez et al. (1993) ; (I ; VBs, O ; *AL*)
ARMA model (Autoregressive Moving-Average, State Space Reconstruction) with inputs of previous measured data
⇒ correlation coefficient ~ 0.91; 15 minutes resolution for 47 hours

Weigel et al. (1999) ; (I ; VBs, O ; *AL*)
gated network with inputs of previous measured data
⇒ correlation coefficient ~ 0.94; 15 minutes resolution for 20 hours

5. Method and Results

1) *Dst* - *AL* Relationship (Shen et al. 2002)
assumptions ; magnetospheric electric field is homogeneous from the injection region through the ring current region



⇒ correlation coefficient of *Dst* ; 0.80 - 0.84 for 1998 & 1999 (1 hour resolution)

2) Temerin and Li (2002) ; *Dst* prediction with empirical model
⇒ correlation coefficient of *Dst* ; 0.941 for 1999 (1 hour resolution)

3) Our model and parameters

$$al(t+dt) = al(t) + \{c_1 \cdot |al(t)|^{c_2} \{1+erf(c_3 \cdot al(t))] + df\{1-erf[c_4 \cdot (b_z(t-\tau_1)+c_5 \cdot |b_z(t-\tau_1)|)]\} [1+c_6 \cdot al(t-\eta_1)]\}[1+c_7 \cdot al(t-\eta_1)]dt$$

$df = c_8 \cdot tst1 \cdot fe/(1-fe)$ (τ_1 = 50 minutes, η_1 = 90 minutes)

$tst1 = (\sin\phi / \sin\phi_o)^{c_9}$

$\sin\phi = (1-\cos^2\phi)^{1/2}$

$\cos\phi = c_{10} \cdot \sin(tt+\alpha) \cdot \sin(ttt-tt-\beta) + \cos(tt+\alpha) \cdot (c_{11} + c_{12} \cdot \cos(ttt-tt-\beta))$

$tt = 2\pi t/\text{year}, \quad ttt = 2\pi t$

$fe = c_{13} \cdot exx \cdot v_x^{c_{14}} \cdot n^{c_{15}} \{1+erf[c_{16} \cdot b_p \cdot \cos(\omega+\omega_o) \cdot dh]\}$

$exx = b_t^{c_{17}} \cdot \sin^{c_{18}}\theta$

$b_t^2 = b_y^2 + b_z^2$

$\theta = \arccos(b_z/b_t)/2$

$b_p^2 = b_x^2 + b_y^2$

$\omega = \arctan(b_x, b_y)$

$dh = c_{19} \cdot \cos(tt+\text{phaseyear}) - \sin(ttt+\text{phase})$

$$esw1(t) = c_{20} \cdot tst2(t-\eta_2) \cdot [zb \cdot bzz(t-\tau_2) + (1-zb) \cdot bzz(t+dt-\tau_2)]$$
$$esw2(t) = esw1(t) \cdot [1 + c_{21} \cdot \sin(tt + c_{22})]$$
$$esw3(t) = c_{23}[esw2(t) + c_{24} - |\, esw2(t) + c_{24} \,|]$$
$$esw(t) = \frac{1}{7}\sum_{i=-3}^{3} esw3(t+\gamma_i)$$

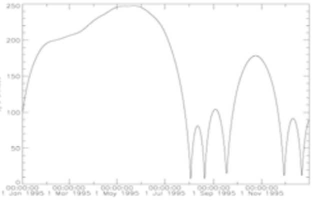
$$tst2 = (\sin\phi / \sin\phi_o)^{c_{25}} \qquad (\eta_2 = 80 \text{ minutes}, \ \tau_2 = 80 \text{ minutes})$$
$$bzz(t) = bz \cdot (c_{26} \cdot v_x)^{c_{27}}$$
$$\gamma_i = 10 \times i \ \text{ minutes}$$

$$als(t) = [al(t) + esw(t)]\{1 + c_{28} \cdot \sin(ttt + c_{29})[1 + c_{30} \cdot \sin(tt + c_{31})]\}[1 + c_{32} \cdot \sin(2ttt + c_{33})]$$

Final *AL* index ;

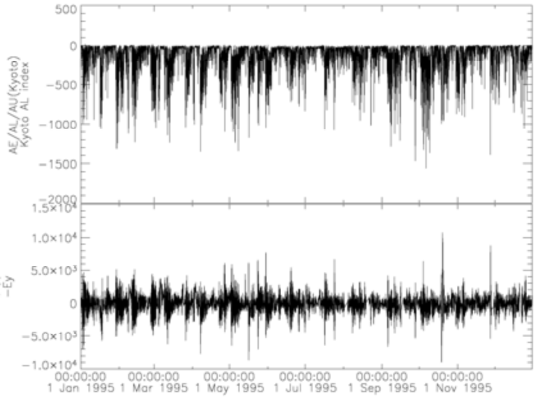
$$AL(t) = \frac{1}{5}\sum_{i=-2}^{2} als(t+\gamma_i)$$

- input ; solar wind ($\vec{v}_{sw}, \vec{b}_{sw}, n$)
- 37 model parameters
- Solar Wind data ;
  - Wind satellite data
  - 10 minutes resolution
  - 7% missing in 1995

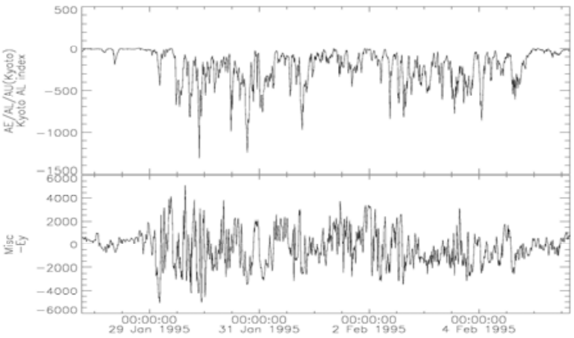


[geocentric distance of WIND]

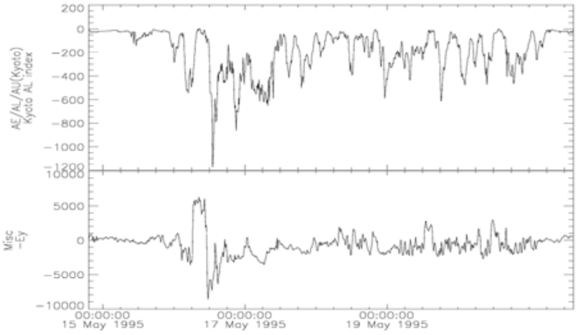
- *AL* data ; World Data Center for Geomagnetism, Kyoto
  - 1995 provisional 1 minute resolution
  - averaged to 10 minutes



AL vs *Ey* ; no time delay - direct drive



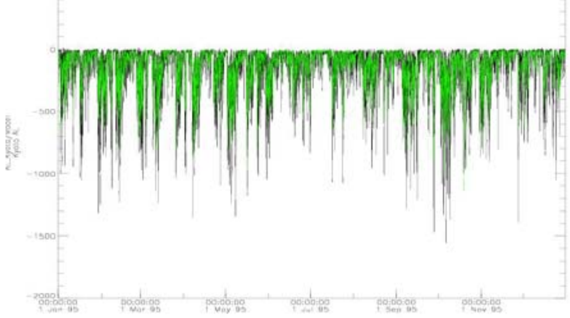
AL vs *Ey* ; time delay , loading – unloading



4) Results

predicted *AL* ; 10 minutes resolution

1995 (93 % of 1 year = 354 days)



predicted *AL* ; 10 minutes resolution

1995 (93 % of 1 year = 354 days)

PE = 0.717 (correlation coefficient ; CC = 0.847)

RMS error = 88.8 nT

[PE = 1 – (mean square of residuals)/(variance of data)]

data ; y_i, $\rightarrow$ mean ; $\bar{y}$

model ; Y_i, $\rightarrow$ mean ; $\bar{Y}$

$$\sigma_y^2 = \frac{\Sigma(y_i - \bar{y})^2}{n-1}$$

$$s_y^2 = \frac{\Sigma(y_i - Y_i)^2}{n-1}$$

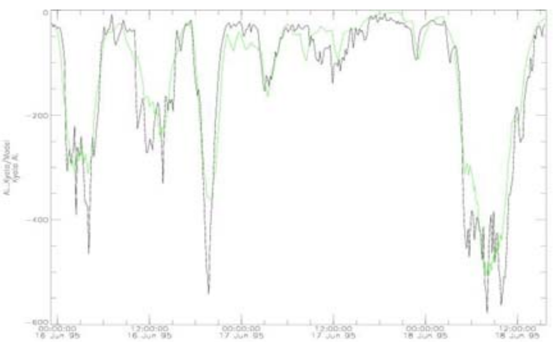
$$\sigma_Y^2 = \frac{\Sigma(Y_i - \bar{Y})^2}{n-1}$$

$$\sigma_{yY} = \frac{\Sigma(y_i - \bar{y})(Y_i - \bar{Y})}{n-1}$$

prediction efficiency; $\mathrm{PE} = 1 - \frac{\sigma_y^2}{s_y^2}$

correlation coefficient; $\mathrm{CC} = \frac{\sigma_{yY}}{\sigma_y \sigma_Y}$

1995/6/16 – 1995/6/18-18h (66 hours)



1995/6/16 – 1995/6/18-18h (66 hours)

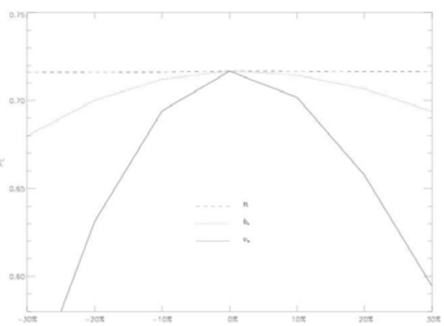
PE = 0.891 (CC = 0.946)

RMS error = 46.2 nT

1995 (93 % of 1 year = 354 days)

PE = 0.717 (correlation coefficient ; CC = 0.847)

RMS error = 88.8 nT



Prediction efficiency dependences on the parameters (1995)

6. Summary and Conclusions

i) An empirical model is applied to predict *AL* index with solar wind inputs.

ii) PE = 0.717 (CC = 0.847) for about one year (10 minutes of resolution)

PE = 0.891 (CC = 0.946) for 66 hours (10 minutes of resolution)

iii) Solar wind velocity and magnetic field influence a lot on *AL* index, but density has small effect on it.

iv) These results indicate that *AL* index is reasonably well predicted by solar wind inputs. So the magnetosphere seems to have an organized response to the solar wind even down to 10 minutes time-scale.