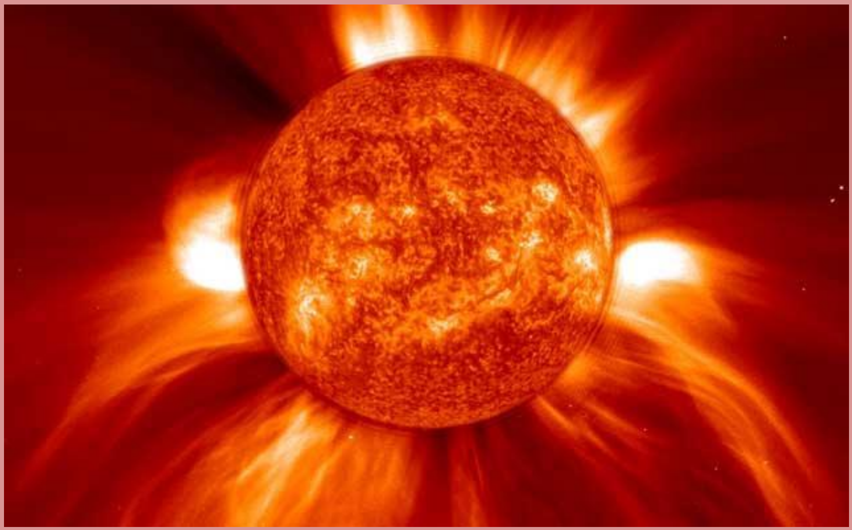
Luleå University of Technology

Space Physics

THE SOLAR WIND



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Space Master Program

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THE SOLAR WIND

1. INTRODUCTION

Solar wind, a gusty stream of plasma travels in all directions from sun at a speed of about 400 km/s. Solar wind is not uniform, it varies in temperature, speed and density.
The Advanced Composition Explorer (ACE) satellite was launched in August of 1997 and placed into an orbit where the gravitational attraction of the Sun and Earth are equal and opposite. This particular point is the Lagrangian 1 (L1) located about 1.5 million km (1 million miles) from the Earth in the direction of the Sun. ACE has a number of instruments that monitor the solar wind and provides real-time information on solar wind conditions as seen by the spacecraft.

2. EXERCISE 1

TASK A. The ACE data are given in the so-called GSE coordinates. What does GSE stand for and how is the coordinate system defined? How does this coordinate system relate to the normal spherical coordinate system with the Sun in the center?

GSE coordinates stands for Geocentric Solar Ecliptic coordinates. This system is fixed with respect to Earth-Sun Line.

X axis = towards the sun from earth (Earth-Sun line)

Z axis = Parallel to Ecliptic North Pole

The Normal spherical coordinates are Sun-centered and inertially fixed with respect to X-axis.

X axis = The Sun-Earth line

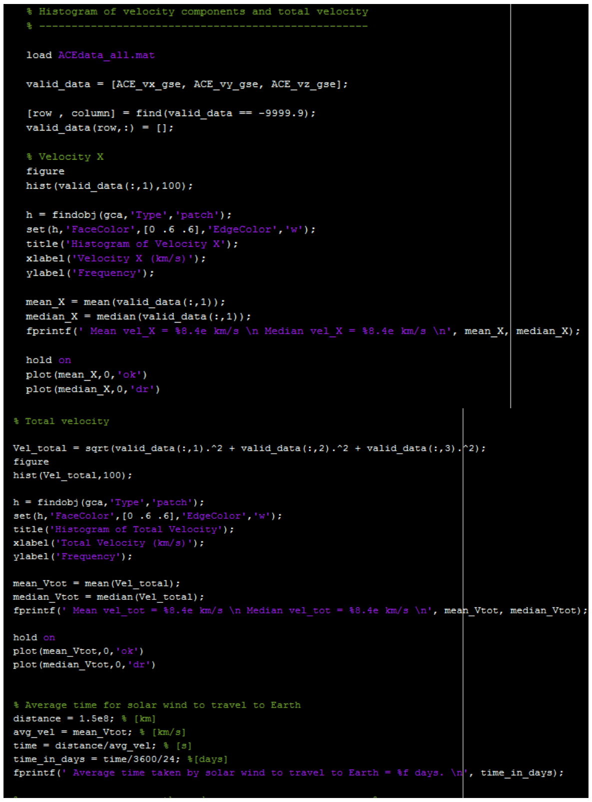
Z axis = Ecliptic North Pole

TASK B. What instrument provides the velocity data? And how does it work? Describe and explain shortly, and give a reference.

SWEPAM (**Solar Wind Electron, Proton, and Alpha Monitor**) provides solar wind velocity data. It uses electrostatic analyzers for ions that measure the energy per charge of each particle. 16 Channel multipliers are located behind the analyzers that look in 16 different directions simultaneously and detects the transmitted ions.
Source: http://swepam.lanl.gov/
http://www.goembel.biz/sun.html

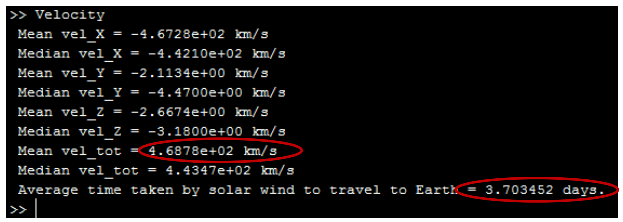
3. EXERCISE 2

TASK A. Make histograms for each velocity component and for the total velocity. In the Figures, mark the mean and median values for |v| or v_x. What are the values? Compare your results with published results. How long does it typically take for the solar wind to reach Earth from the Sun?



```
% Histogram of velocity components and total velocity
% ---------------------------------------------------

load ACEdata_all.mat

valid_data = [ACE_vx_gse, ACE_vy_gse, ACE_vz_gse];

[row , column] = find(valid_data == -9999.9);
valid_data(row,:) = [];

% Velocity X
figure
hist(valid_data(:,1),100);

h = findobj(gca,'Type','patch');
set(h,'FaceColor',[0 .6 .6],'EdgeColor','w');
title('Histogram of Velocity X');
xlabel('Velocity X (km/s)');
ylabel('Frequency');

mean_X = mean(valid_data(:,1));
median_X = median(valid_data(:,1));
fprintf(' Mean vel_X = %8.4e km/s \n Median vel_X = %8.4e km/s \n', mean_X, median_X);

hold on
plot(mean_X,0,'ok')
plot(median_X,0,'dr')

% Total velocity

Vel_total = sqrt(valid_data(:,1).^2 + valid_data(:,2).^2 + valid_data(:,3).^2);
figure
hist(Vel_total,100);

h = findobj(gca,'Type','patch');
set(h,'FaceColor',[0 .6 .6],'EdgeColor','w');
title('Histogram of Total Velocity');
xlabel('Total Velocity (km/s)');
ylabel('Frequency');

mean_Vtot = mean(Vel_total);
median_Vtot = median(Vel_total);
fprintf(' Mean vel_tot = %8.4e km/s \n Median vel_tot = %8.4e km/s \n', mean_Vtot, median_Vtot);

hold on
plot(mean_Vtot,0,'ok')
plot(median_Vtot,0,'dr')


% Average time for solar wind to travel to Earth
distance = 1.5e8; % [km]
avg_vel = mean_Vtot; % [km/s]
time = distance/avg_vel; % [s]
time_in_days = time/3600/24; %[days]
fprintf(' Average time taken by solar wind to travel to Earth = %f days. \n', time_in_days);
```

(a)



```
>> Velocity
 Mean vel_X = -4.6728e+02 km/s
 Median vel_X = -4.4210e+02 km/s
 Mean vel_Y = -2.1134e+00 km/s
 Median vel_Y = -4.4700e+00 km/s
 Mean vel_Z = -2.6674e+00 km/s
 Median vel_Z = -3.1800e+00 km/s
 Mean vel_tot = 4.6878e+02 km/s
 Median vel_tot = 4.4347e+02 km/s
 Average time taken by solar wind to travel to Earth = 3.703452 days.
>>
```

(b)

Figure 2.1: (a) Matlab code to make histogram for each velocity component & total velocity and (b) Computed results for velocity.

According to the text book "Introduction to Space Physics by Margaret G. Kivelson & Christopher T. Russell", mean velocity of solar wind should be 450 km/s and our computed mean velocity result is 468 km/s which is approximately same.

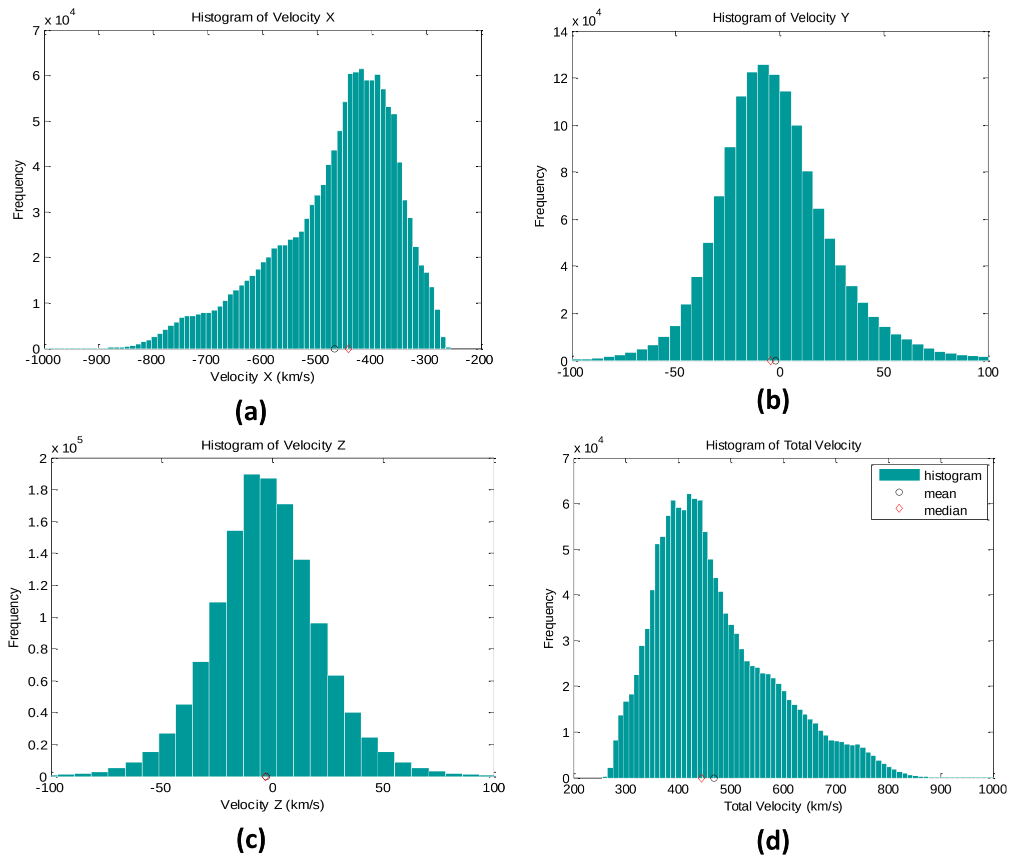
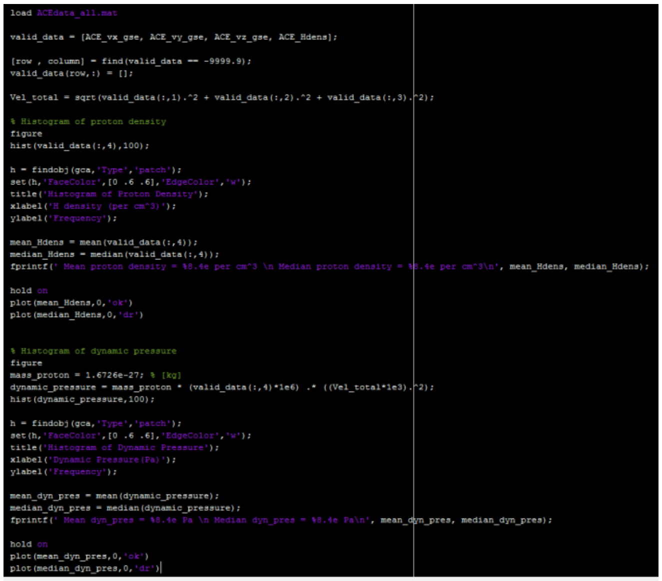


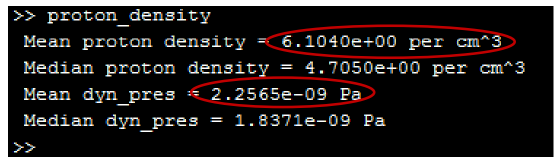
Figure 2.2: Histogram of velocity (a) X-Component (b) Y-Component (c) Z-Component & (d) Total Velocity.

It typically takes 3.7 days for the solar wind to reach Earth from the Sun as per our results for L1 point and according to the text book, time taken by solar wind from corona to earth (1 AU) is 4 days. All the results shown in above Figure 2.1 (b) and Figure 2.2.

TASK B. Make histograms for the proton density and the dynamic pressure, and mark the mean and median values. What are the values? Compare your results with published results.



```
load ACEdata_all.mat

valid_data = [ACE_vx_gse, ACE_vy_gse, ACE_vz_gse, ACE_Hdens];

[row , column] = find(valid_data == -9999.9);
valid_data(row,:) = [];

Vel_total = sqrt(valid_data(:,1).^2 + valid_data(:,2).^2 + valid_data(:,3).^2);

% Histogram of proton density
figure
hist(valid_data(:,4),100);

h = findobj(gca,'Type','patch');
set(h,'FaceColor',[0 .6 .6],'EdgeColor','w');
title('Histogram of Proton Density');
xlabel('H density (per cm^3)');
ylabel('Frequency');

mean_Hdens = mean(valid_data(:,4));
median_Hdens = median(valid_data(:,4));
fprintf(' Mean proton density = %8.4e per cm^3 \n Median proton density = %8.4e per cm^3\n', mean_Hdens, median_Hdens);

hold on
plot(mean_Hdens,0,'ok')
plot(median_Hdens,0,'dr')


% Histogram of dynamic pressure
figure
mass_proton = 1.6726e-27; % [kg]
dynamic_pressure = mass_proton * (valid_data(:,4)*1e6) .* ((Vel_total*1e3).^2);
hist(dynamic_pressure,100);

h = findobj(gca,'Type','patch');
set(h,'FaceColor',[0 .6 .6],'EdgeColor','w');
title('Histogram of Dynamic Pressure');
xlabel('Dynamic Pressure(Pa)');
ylabel('Frequency');

mean_dyn_pres = mean(dynamic_pressure);
median_dyn_pres = median(dynamic_pressure);
fprintf(' Mean dyn_pres = %8.4e Pa \n Median dyn_pres = %8.4e Pa\n', mean_dyn_pres, median_dyn_pres);

hold on
plot(mean_dyn_pres,0,'ok')
plot(median_dyn_pres,0,'dr')
```



```
>> proton_density
 Mean proton density = 6.1040e+00 per cm^3
 Median proton density = 4.7050e+00 per cm^3
 Mean dyn_pres = 2.2565e-09 Pa
 Median dyn_pres = 1.8371e-09 Pa
>>
```

(a) (b)

Figure 2.3: (a) Matlab code to make histogram for Proton density & the Dynamic Pressure and (b) Computed results for Proton density and Dynamic Pressure.

The initial plots were done on a linear scale and similar to the case of velocity analysis most of the graph appeared empty. Therefore to have a better understanding of the values, the values are plotted again logarithmically (base 10) as the range of values was huge.

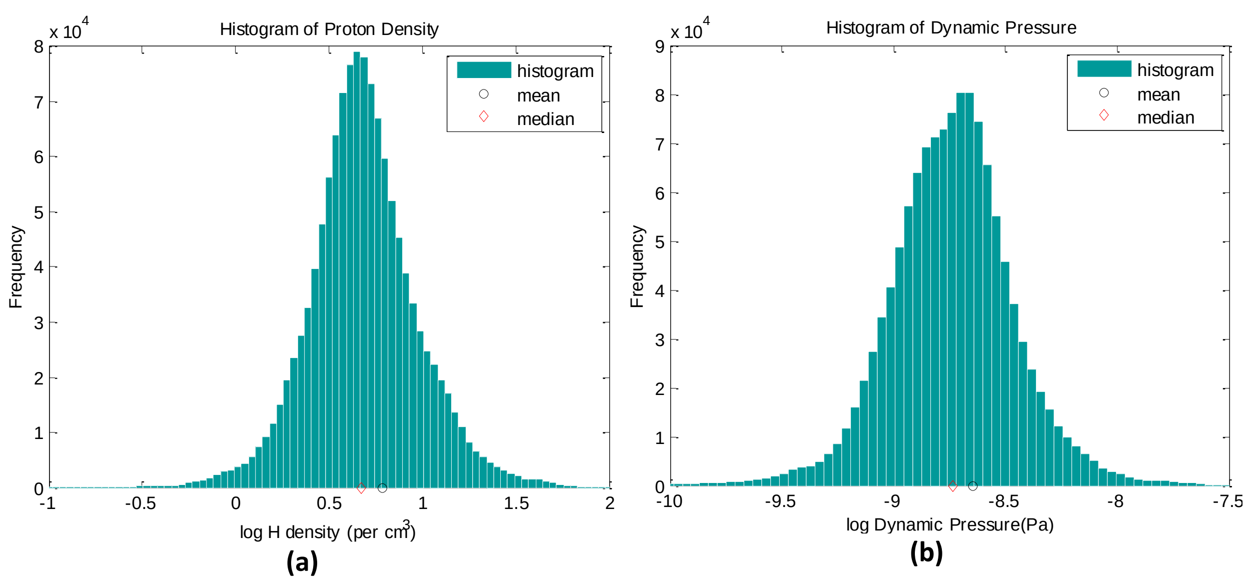


Figure 2.4: Histogram for (a) Proton Density & (b) Dynamic Pressure.

We have got mean proton density 6.1 /cm^3 which is shown in Figure 2.4 (b) and the published data indicates the value is 6.6 /cm^3.

The equation for dynamic pressure of protons is,

$$P = 1.6726 * 10^{-6} * n * v^2 \tag{1}$$

Where, P is Dynamic pressure
n is Proton density, and
v is Solar wind velocity

We calculated the ideal dynamic pressure using equation (1) with the published ideal values of proton density (6.6 /cm^3) and solar wind velocity (450 km/s) at 1AU. This value turns out to be 2.2354 nPa. The calculated mean dynamic pressure of 2.2565 nPa using ACE data is quite similar to the ideal value. This can be seen in Figure 2.3 (b).

TASK C. Make histograms for each B-Field component and for the total field strength. Explain the distributions of the B-Field components. In the Figure, mark the mean and median values for |B|. What are the values? Compare your results with published results. Also, calculate the IMF spiral angles and present the results as a histogram, covering -180 to +180 degrees. If done correctly there will be two peaks, mark these peaks and present the corresponding angles. Are they what you expect? Provide a picture where you clearly define the IMF spiral angle, and discuss the results in relation to the Figure.

The computed magnetic field is 7.325 nT and text book represents 7 nT. The results are shown in Figure 2.5 (b) and 2.6.

```
% Histogram of each B-field component and total B-field
% -------------------------------------------------------

load ACEdata_all.mat

valid_B_field = [ACE_Bx_gse, ACE_By_gse, ACE_Bz_gse];

invalid_B_position = (valid_B_field == -9999.9);
[row , column] = find(invalid_B_position);
valid_B_field(row,:) = [];


% B-field X
figure
hist(valid_B_field(:,1),100);

h = findobj(gca,'Type','patch');
set(h,'FaceColor',[0 .6 .6],'EdgeColor','w');
title('Histogram of B-field X');
xlabel('B-field X (nT)');
ylabel('Frequency');

mean_B_X = mean(valid_B_field(:,1));
median_B_X = median(valid_B_field(:,1));
fprintf(' Mean B_X = %8.4e nT \n Median B_X = %8.4e nT \n', mean_B_X, median_B_X);

hold on
plot(mean_B_X,0,'ok')
plot(median_B_X,0,'dr')
```

(a)

```
>> B_field
 Mean B_X = -1.0039e-01 nT
 Median B_X = -2.0300e-01 nT
 Mean B_Y = 4.3905e-02 nT
 Median B_Y = 1.2600e-01 nT
 Mean B_Z = -2.6320e-02 nT
 Median B_Z = -1.3000e-02 nT
 Mean B_tot = 7.3250e+00 nT
 Median B_tot = 6.4907e+00 nT
>>
```

(b)

Figure 2.5: (a) Matlab code to make histogram for B-field & (b) Results of B-field components.

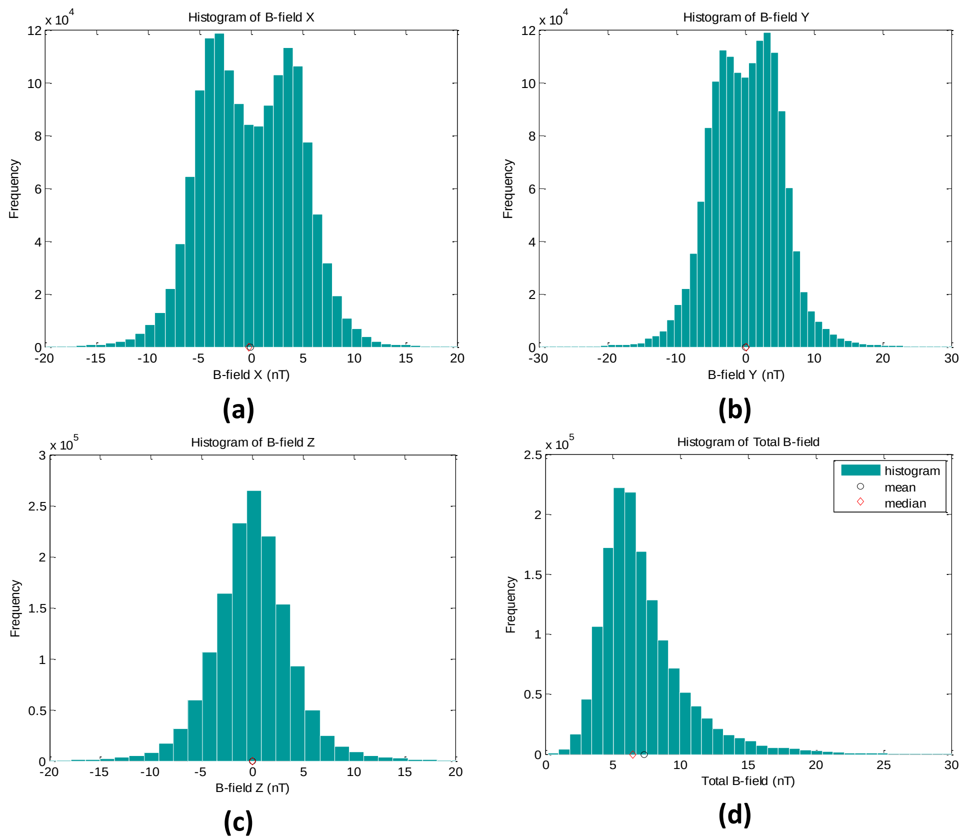


Figure 2.6: Histogram for B-field (a) X-component (b) Y-Component (c) Z-Component & (d) Total B-field.

IMF SPIRAL ANGLE

IMF stands for Interplanetary Magnetic Field. It originates from the Sun and travels in space via solar wind. This magnetic field is spiral in shape because of the rotation of Sun given by the Parker's spiral. At 1AU distance, solar wind velocity is approximately 400 km/sec, so the average spiral angle is about 45 degrees.

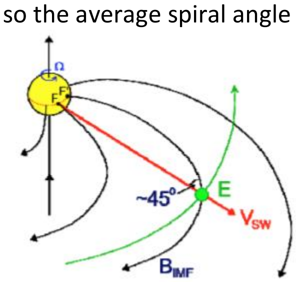


Figure 2.7: IMF Spiral angle.
Source: http://ham.space.umn.edu/cattell/PHYS4611/lecture_5oct.pdf

The equation for calculating IMF Spiral angle is –

$$\alpha = \tan^{-1}\frac{B_y}{B_x} = \frac{\omega r}{v_{sw}} \qquad (2)$$

Where α is IMF spiral angle

B_y is the magnetic field in y – direction

B_x is the magnetic field in x – direction

ω is angular velocity of solar rotation ($\omega = 2.7 * 10^{-6}$ rad sec^{-1})

r is the distance between earth and sun (0.99 AU at L1), &

v_{sw} is the average velocity of solar wind (450 km/s)

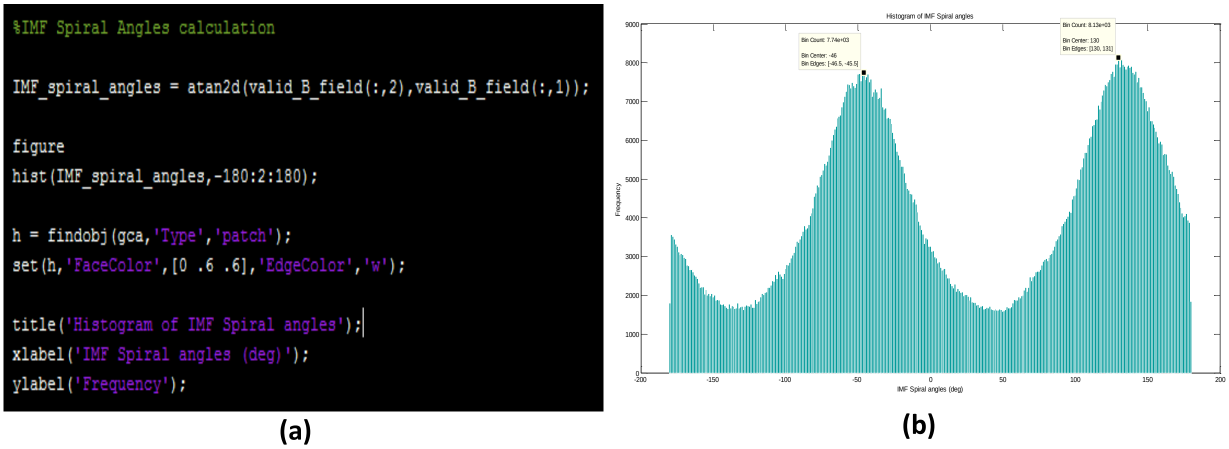


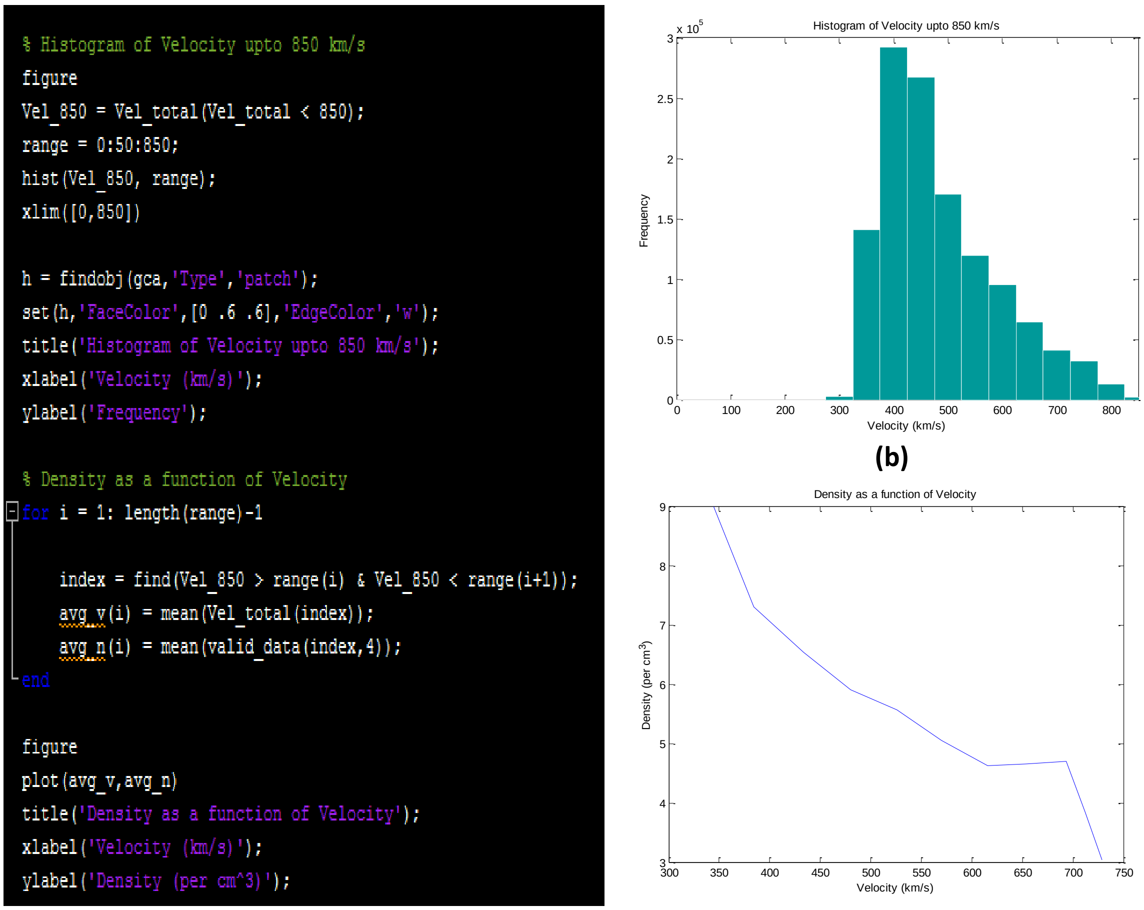
Figure 2.8: (a) Matlab code for IMF Spiral angles calculation & (b) Histogram for IMF spiral angles.

The two peaks of IMF spiral angles are observed at α = -46 & 130 degrees. These are approximately 180 degrees apart and this shows the flip in the direction of magnetic field lines observed due to the fluctuating nature of solar wind parameters.

Ideal value from equation (2) of IMF spiral at L1 can be calculated as, α = 41.7 degree. So the result obtained is closed to this value and can be shown in Figure 2.8 (b).

TASK D. Calculate the density as a function of velocity (up to 850 km/s). Do you see a correlation? If so, discuss the result shortly. Hint: divide the data into velocity intervals (e.g. 0-50 km/s; 50-100 km/s etc), and calculate the average velocity and corresponding density for each interval, and then plot these averages.

Figure 2.9 (b) shows the histogram of velocity intervals upto 850 km/s split into 50 km/s bins. Figure 2.10 (b) shows density as a function of velocity. The curve is seen to decrease with increase in velocity. Thus they are inversely related.



(a) (b) (c)

Figure 2.9: (a) Matlab code for histogram of velocity up to 850 km/s & density as a function of velocity and (b) Histogram for velocity upto 850 km/s & (c) Density as a function of velocity.

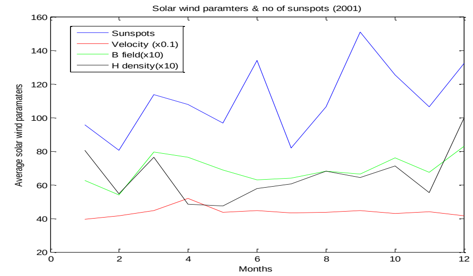
4. EXERCISE – 3

TASK A. Plot monthly averages of the solar wind characteristics (|v|, n_H and |B|) and the monthly sunspots. Can you see any correlation between sunspot number and any of the solar wind parameters?

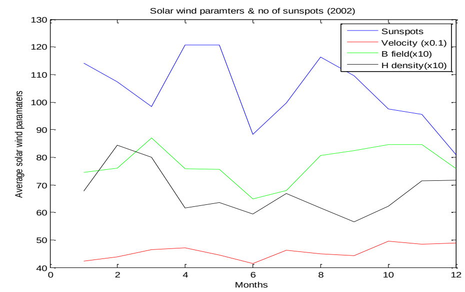
The monthly averages for the solar wind parameters have been plotted (Figure 3.1) and tabulated (Table – 3.1).

```
% Correlation between Solar activity and solar wind properties

load sunspots_month.mat
load ACEdata_all.mat

valid_data = [ACE_vx_gse,...
              ACE_vy_gse,...
              ACE_vz_gse,...
              ACE_Hdens,...
              ACE_Bx_gse,...
              ACE_By_gse,...
              ACE_Bz_gse,...
              ACE_mattime];

[row , column] = find(sunspots(:,1) > 2003);    % extracting data from 2001 to 2003
sunspots(row,:) = [];

[row , column] = find(valid_data == -9999.9);   % extracting valid data
valid_data(row,:) = [];

Vel_total = sqrt(valid_data(:,1).^2 + valid_data(:,2).^2 + valid_data(:,3).^2);
Hdens = valid_data(:,4);
B_total = sqrt(valid_data(:,5).^2 + valid_data(:,6).^2 + valid_data(:,7).^2);

time_values = valid_data(:,8);
dates_str = datestr(time_values, 'dd,mm,yyyy');
dates_num = str2num(dates_str);

 % Average solar wind parameters

 year = 2001;
for i = 1:3

    for j = 1:12
        index = find(dates_num(:,2) == j & dates_num(:,3) == year);
        avg_v(j,i) = mean(Vel_total(index));
        avg_B(j,i) = mean(B_total(index));
        avg_n(j,i) = mean(Hdens(index));
    end
    year = year + 1;

end

 months = {'Jan', 'Feb', 'Mar', 'Apr', 'May', 'Jun', 'Jul', 'Aug', 'Sep', 'Oct', 'Nov',

 T = table(avg_v(:,1),avg_v(:,2),avg_v(:,3),...
          avg_B(:,1),avg_B(:,2),avg_B(:,3),...
          avg_n(:,1),avg_n(:,2),avg_n(:,3),'RowNames',months);

 T.Properties.VariableNames = {'Y_2001_v','Y_2002_v','Y_2003_v',...
                              'Y_2001_B','Y_2002_B','Y_2003_B',...
                              'Y_2001_n','Y_2002_n','Y_2003_n'};


 disp(T)
```

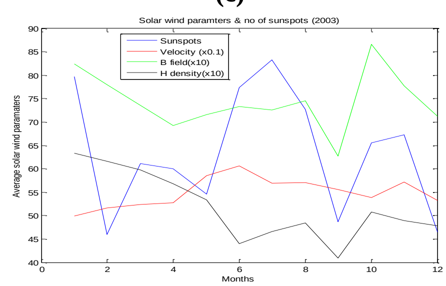
(a)



(b)



(c)



(d)

Figure 3.1: (a) Matlab code for Monthly average Solar wind parameters and Plot for Solar wind parameters & number of sunspots for year (b) 2001 (c) 2002 & (d) 2003.

Table 3.1 – Monthly averages of Solar wind parameters for year 2001, 2002 & 2003

```
>> Solar_activity
```

	Y_2001_v	Y_2002_v	Y_2003_v	Y_2001_B	Y_2002_B	Y_2003_B	Y_2001_n	Y_2002_n	Y_2003_n
Jan	396.04	423.38	498.76	6.2592	7.4549	8.2483	8.0513	6.7755	6.3318
Feb	414.75	438.51	516.33	5.4001	7.5966	7.804	5.4613	8.4407	6.1623
Mar	447.46	465.38	524.3	7.9378	8.6928	7.3613	7.6229	7.9949	5.9789
Apr	519.79	472.02	527.42	7.6395	7.5872	6.9295	4.8319	6.147	5.6836
May	435.69	444.05	585.12	6.8936	7.5627	7.154	4.739	6.3588	5.336
Jun	445.46	414.44	606.7	6.282	6.4816	7.3304	5.7911	5.9278	4.3949
Jul	432.88	461.78	569.8	6.3981	6.783	7.2633	6.0684	6.6902	4.66
Aug	435.9	450.15	570.12	6.818	8.055	7.4605	6.799	6.1535	4.8416
Sep	446.44	443.34	556.11	6.6249	8.2291	6.2698	6.4361	5.6446	4.0932
Oct	428.85	495.49	538.74	7.6022	8.4487	8.6599	7.1144	6.2232	5.0786
Nov	440.8	484.3	571.68	6.7377	8.4566	7.7698	5.5374	7.1437	4.892
Dec	414.07	487.8	532.88	8.2841	7.5811	7.1201	9.9868	7.1582	4.7764

```
>> |
```

From the Figure 3.1 (b) (c) & (d) the correlation between the solar wind parameters and the number of sunspots is not immediately obvious. Therefore we did the simple analysis by finding the mathematical correlation coefficient which gives us a picture of the linear interdependence for the respective data sets. In the first approach we did the yearly analysis and calculated the correlation coefficient between the monthly averages of sunspot numbers and v, B & n_H individually.

```
% Finding correlation coefficients for each set of data with no. of sunspots

% for year 2001
r11 = corrcoef(T.Y_2001_v, sunspots(1:12,3));   % Velocity
r12 = corrcoef(T.Y_2001_B, sunspots(1:12,3));   % B-field
r13 = corrcoef(T.Y_2001_n, sunspots(1:12,3));   % H density

% for year 2002
r21 = corrcoef(T.Y_2002_v, sunspots(13:24,3));
r22 = corrcoef(T.Y_2002_B, sunspots(13:24,3));
r23 = corrcoef(T.Y_2002_n, sunspots(13:24,3));

% for year 2003
r31 = corrcoef(T.Y_2003_v, sunspots(25:36,3));
r32 = corrcoef(T.Y_2003_B, sunspots(25:36,3));
r33 = corrcoef(T.Y_2003_n, sunspots(25:36,3));

T2 = table({r11(2); r21(2); r31(2)},...
           {r12(2); r22(2); r32(2)},...
           {r13(2); r23(2); r33(2)},'RowNames',{'Y_2001','Y_2002','Y_2003'});

T2.Properties.VariableNames = {'Velocity','B_field','H_density'};

disp(T2)

% Finding correlation coefficient for overall data

D = [[T.Y_2001_v; T.Y_2002_v; T.Y_2003_v], sunspots(:,3)];  % Velocity
r_V = corrcoef(D);

E = [[T.Y_2001_B; T.Y_2002_B; T.Y_2003_B], sunspots(:,3)];  % B-field
r_B = corrcoef(E);

F = [[T.Y_2001_n; T.Y_2002_n; T.Y_2003_n], sunspots(:,3)];  % H density
r_n = corrcoef(F);

T3 = table({r_V(2)}, {r_B(2)}, {r_n(2)},'RowNames',{'Corr. Coeff.'});

T3.Properties.VariableNames = {'Velocity','B_field','H_density'};

disp(T3)
```

Figure 3.2: Matlab code for finding correlation coefficients between Solar wind parameters & Number of sunspots.

Table 3.2 – Correlation coefficients between solar wind parameters & sunspot numbers

	Velocity	B_field	H_density
Y_2001	[0.1631]	[0.4434]	[0.3415]
Y_2002	[-0.3127]	[0.0990]	[-0.2309]
Y_2003	[0.2668]	[0.3695]	[-0.0612]

(a) Each year

	Velocity	B_field	H_density
Corr. Coeff.	[-0.6724]	[0.0709]	[0.5056]

(b) Overall data

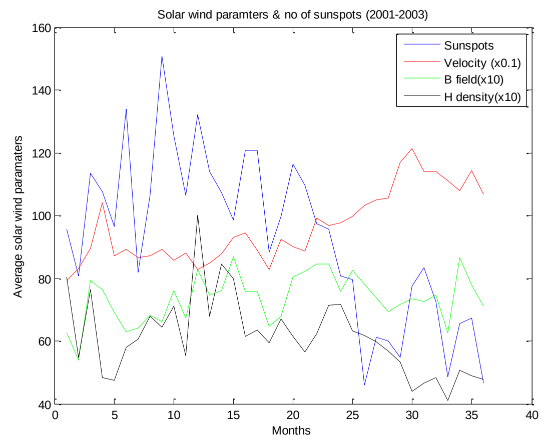


Figure 3.3: Plot of average solar wind parameters and number of sunspots (2001-2003).

From Table 3.2 (a), for the year 2001, B-field appears to be most closely correlated with the sunspot number as compared to velocity and proton density. In addition they are all positively correlated. However in 2002 B-field appears to be barely correlated to the sunspot number and velocity and proton density turn out to be negatively correlated to the sunspot number. And again in the year 2003, completely different pattern of correlation is observed. Hence from this approach the correlation between the solar wind parameters and sunspot numbers is inconclusive.

In the second approach, we calculated the correlation coefficient for the entire data set ranging from year 2001-2003. The results obtained are shown in Table 3.2 (b) and Figure 3.3. From this consolidated analysis proton density has the highest positive correlation coefficient with sunspot number, B-field negligible, and velocity significantly correlated but inversely. Since the yearly variation and the overall variation of solar wind parameters with the sunspot number are discrepant, we cannot confirm that the results obtained in Table 3.2 (b) can be interpolated and seen as a definite pattern of variation.

5. REFERENCES

[1]. Smith, J. W., Acuna, M. H., Burlaga, L. F., LHeureux, J., Ness, N. F., and Scheifele, J.: The ACE magnetic fields experiment, Space Science Reviews, 86, 613632, doi:10.1023/A: 560 1005092216668, 1998.

[2]. Stone, E. C., Christian, E. R., Frandsen, E. C., Margolies, D., Mewaldt, R. A., Ormes, J. F., and Snow, F.: The Advanced Composition Explorer, Space Science Reviews, 86, 122, doi: 10.1023/A:1005082526237, 1998.

[3]. Margaret G. Kivelson, Christopher T. Russell, “Introduction to Space Physics” Cambridge University Press, Apr 28, 1995 - Science - 568 pages