Consequences of the Force-Free Model of Magnetic Clouds for their Heliospheric Evolution

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M. Leitner[1], C. J. Farrugia[2], C. Möstl[1], K. W. Ogilvie[3], A. B. Galvin[2], R. Schwenn[4], and H. K. Biernat[1]

[1] Space Research Institute, Austrian Academy of Sciences, Graz, Austria

[2] Space Science Center, University of New Hampshire, Durham, NH, USA

[3] NASA Goddard Space Flight Center, Greenbelt, MD., USA

[4] Max Planck Institute for Solar System Research, Kathlenburg-Lindau, Germany

1. Aims of the Study

- In **three approaches**, we examine the implications for the heliospheric evolution of magnetic clouds (MCs) of the force–free, constant–alpha flux rope model of these structures, with special emphasis on the inner ($\leq$1 AU) heliosphere.

- Dataset: 130 MC observations from Helios 1, 2 between 0.3–1 AU, and WIND at 1 AU in the same phase of the solar cycle. We supplement these data by observations from other spacecraft (e.g. Voyagers 1, 2, Pioneers 10, 11, and others).

- Obtain **scaling factors** using power law fits.

- In the **first approach**, we work with ensemble averages, binning the data into radial segments of width 0.1 AU.
  [Statistical]

- In the **second approach**, we capture snapshots of MC evolution through several spacecraft line-ups, when the same MC is seen at different heliospheric distances, r_h.
  [single events]

- In the **third approach**, we examine the predictions of an analytical expression for a freely-expanding *Lundquist* (1950) magnetic flux tube, and compare with the other approaches.
  [model]

- Useful background to the STEREO mission and to multi-spacecraft studies of magnetic clouds.

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Constant-α, Force-Free Model of MCs: $\nabla \times \mathbf{B} = \alpha \mathbf{B}$

• Configurations in which a magnetic field of above-average strength rotates through a large angle in a plasma of low proton β (*Burlaga et al.*, 1981). Their expansion was first discussed by *Klein and Burlaga* (1982).

• It was proposed by *Burlaga* (1988) and first elaborated by *Lepping et al.* (1990) that a MC may be considered in a first approximation as force-free, constant-α configuration of locally straight cylindrical geometry of circular cross-section. Very successful in interpretation of observations.

• Solution in cylindrical coordinates (*Lundquist*, 1950):

$$B_{AX} = B_0 J_0(\alpha R) \text{ (axial)}$$
$$B_{AZ} = H B_0 J_1(\alpha R) \text{ (azimuthal)}$$

B_0: Maximum field strength (on axis); B_{AX}, B_{AZ}: axial and azimuthal fields, respectively; $\alpha = 2.4/R_0$ (R_0 = tube radius); $0 \leq R \leq R_0$, radial distance from axis; H = magnetic helicity ($= \pm 1$).

Least-squares fit to the data. Output:

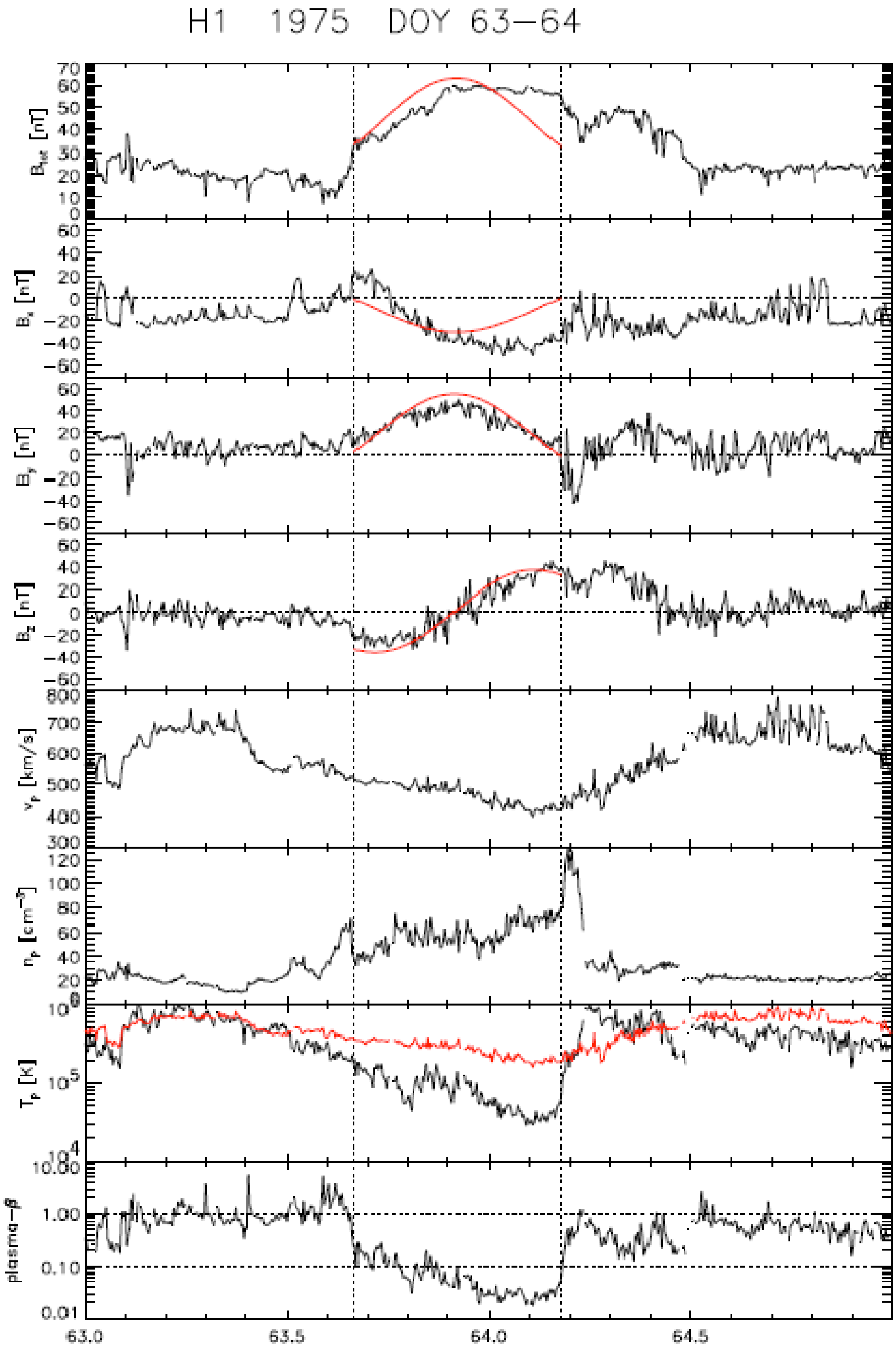
B_0, field strength on the fluxrope axis.

(θ [lat.], ϕ, [long.] SE): Orientation of flux tube axis.

p = distance of spacecraft from axis at closest approach ("impact parameter") and

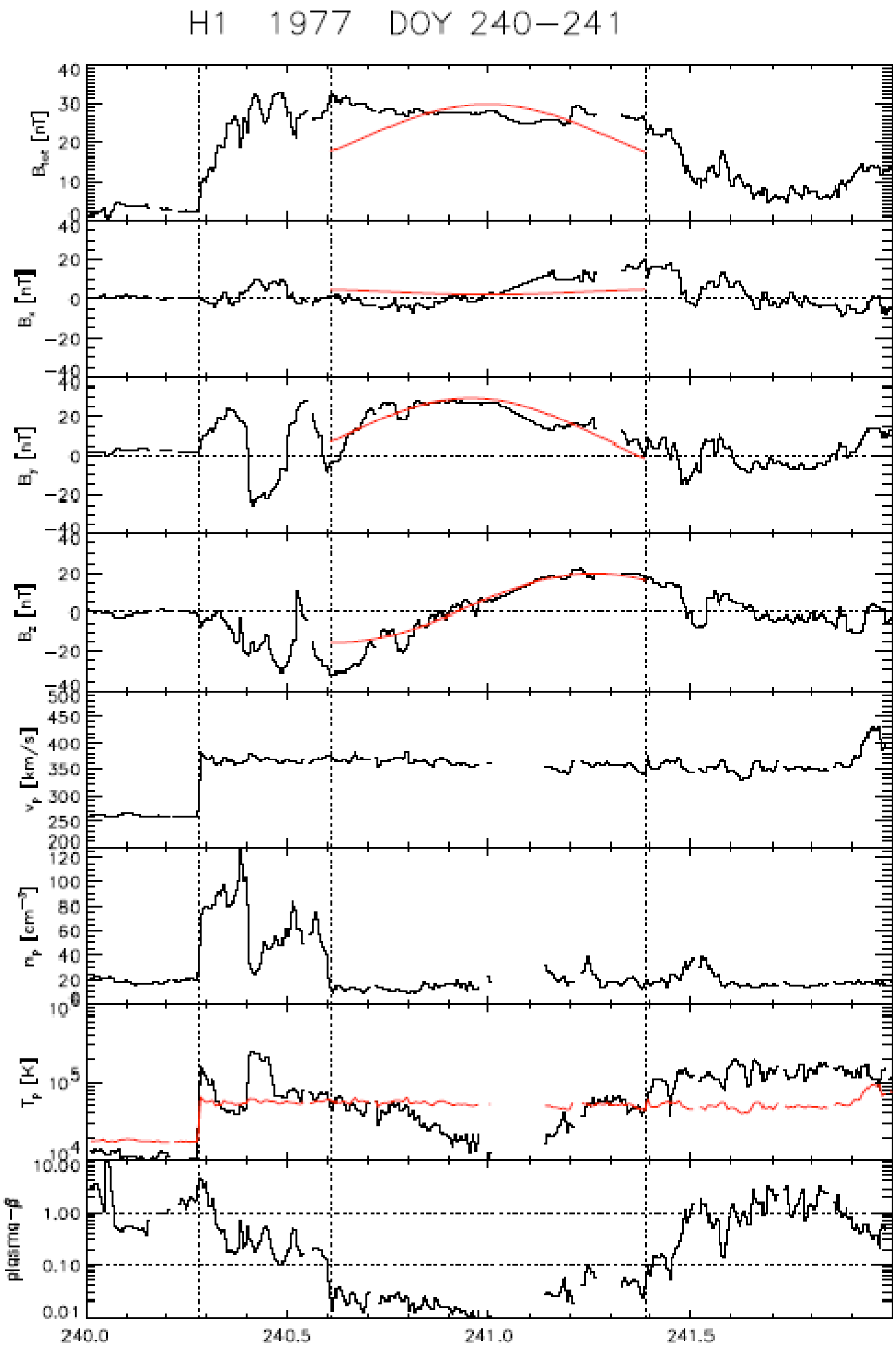
H = magnetic helicity (handedness)

In combination with axis orientation (θ, ϕ), p gives model Diameter of fluxrope. (Model + Geometry).



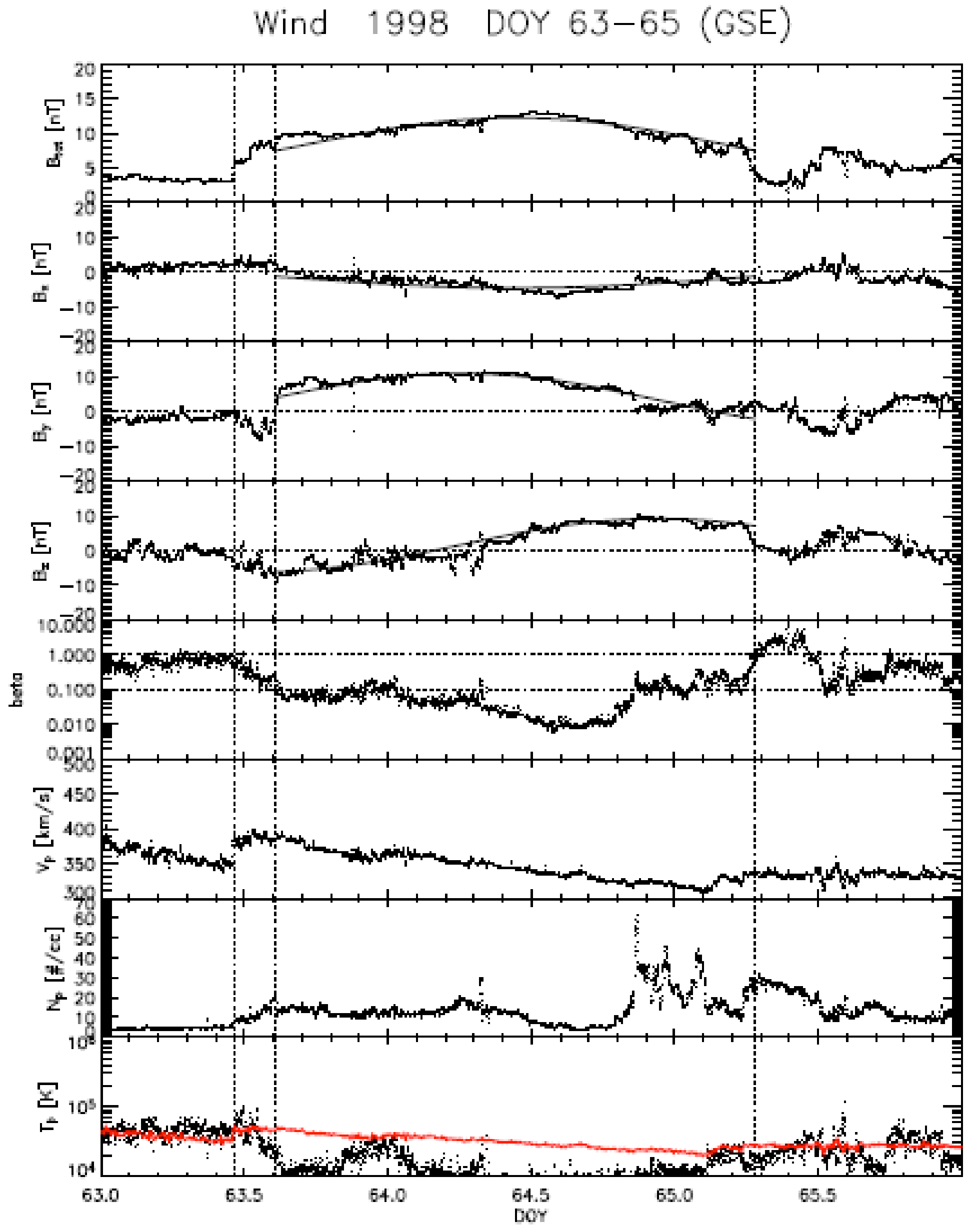
B_0=63 nT, ϕ = 118.8°, θ = 2.1°, p = 0.00R_c, H = -1

0.39 AU



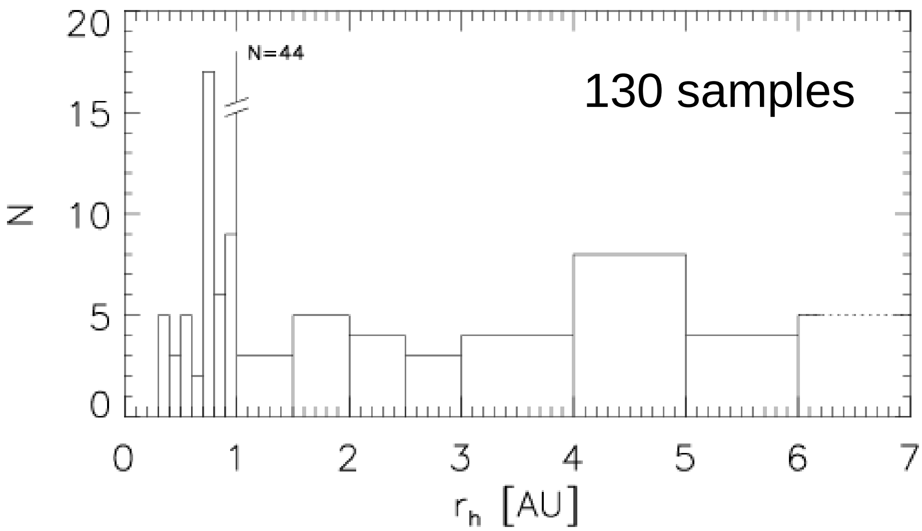
B_0=32.8 nT, ϕ = 108.5°, θ = 12.6°, p = 0.31R_c, H = -1

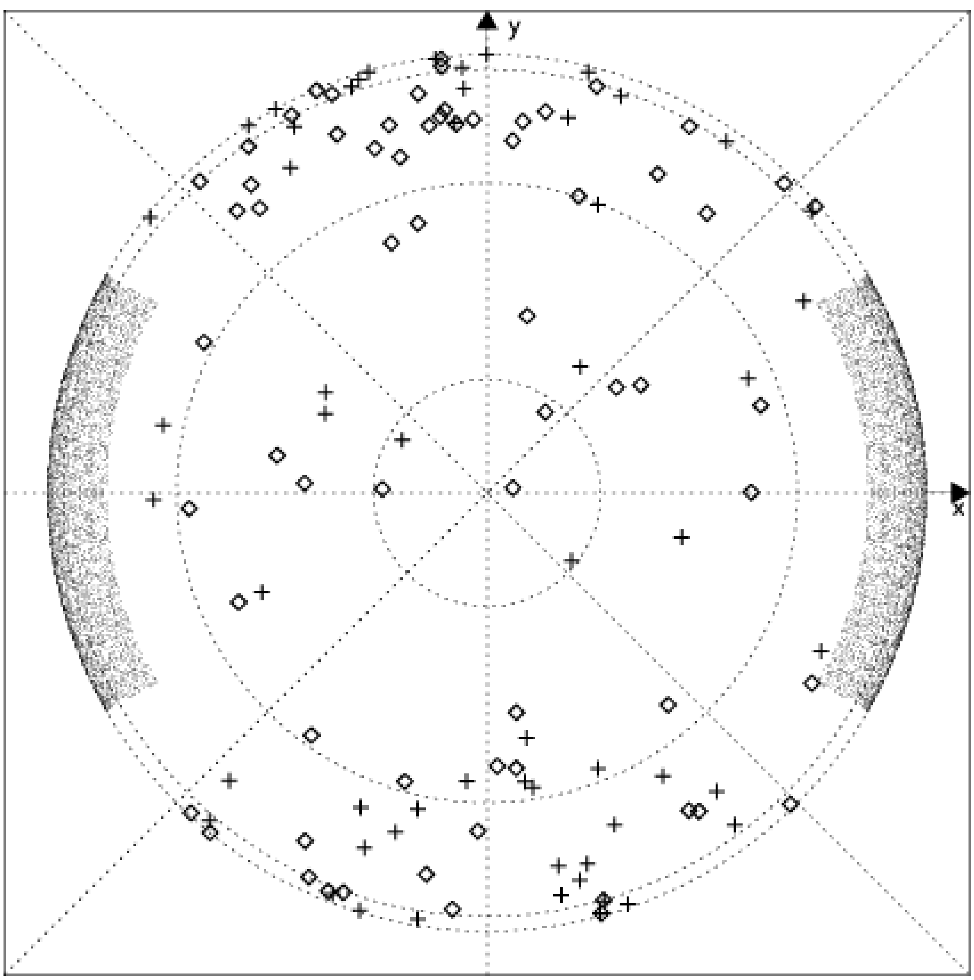
0.85 AU

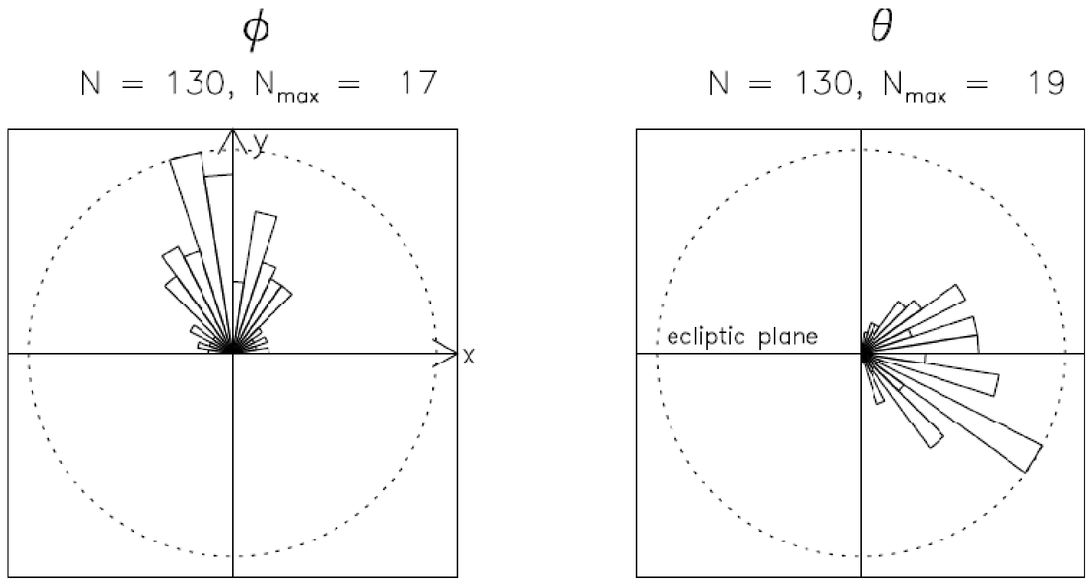


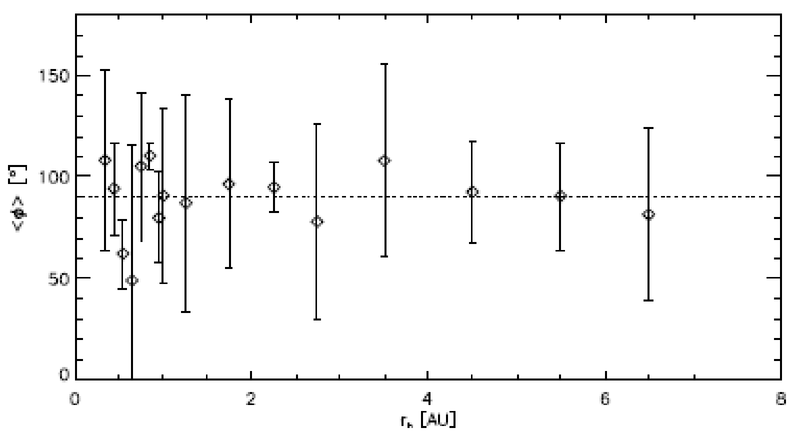
B_0=13.4 nT, ϕ = 105.4°, θ = 56.6°, p = 0.28R_c, H = -1

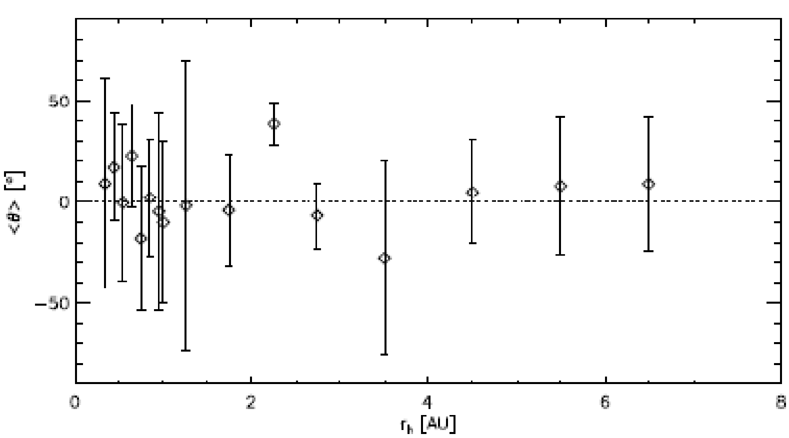
1.0 AU

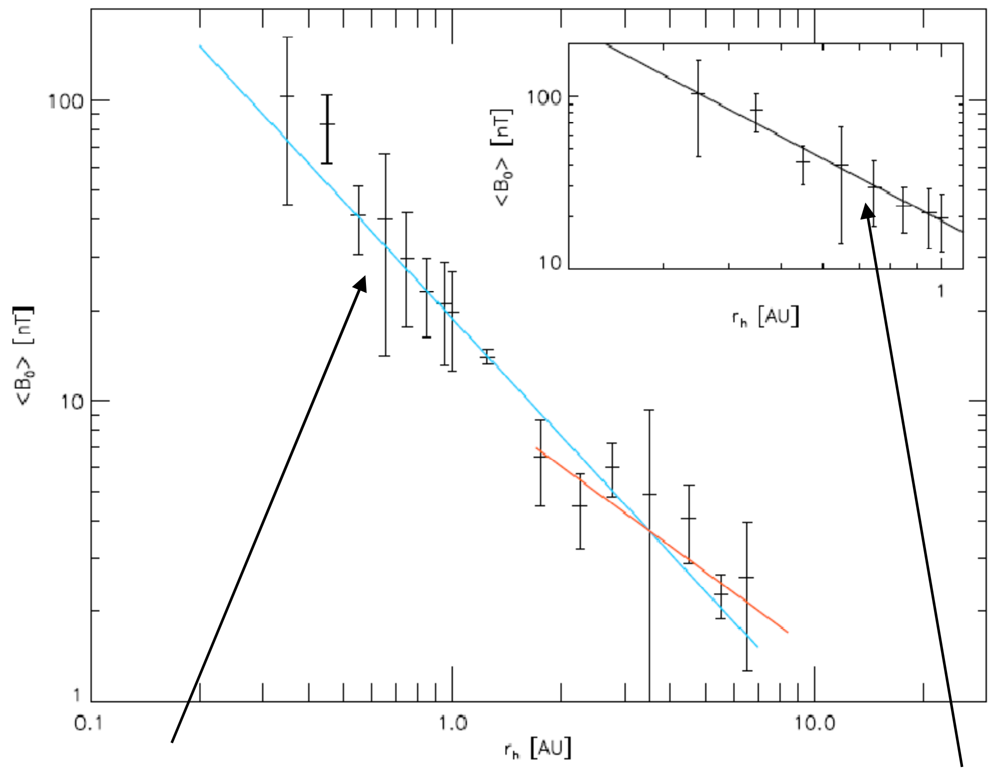

130 samples
N=44
N
r_h [AU]
0
5
10
15
20
0
1
2
3
4
5
6
7


y
x


φ
N = 130, N_max = 17
y
x
θ
N = 130, N_max = 19
ecliptic plane

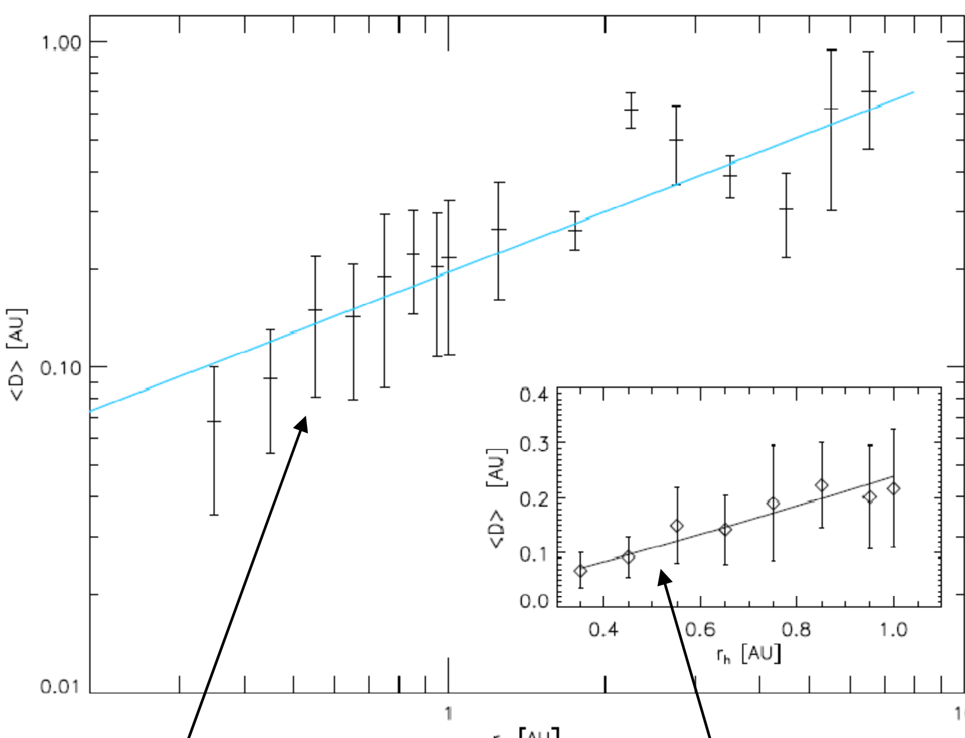

<φ> [°]
r_h [AU]


<θ> [°]
r_h [AU]



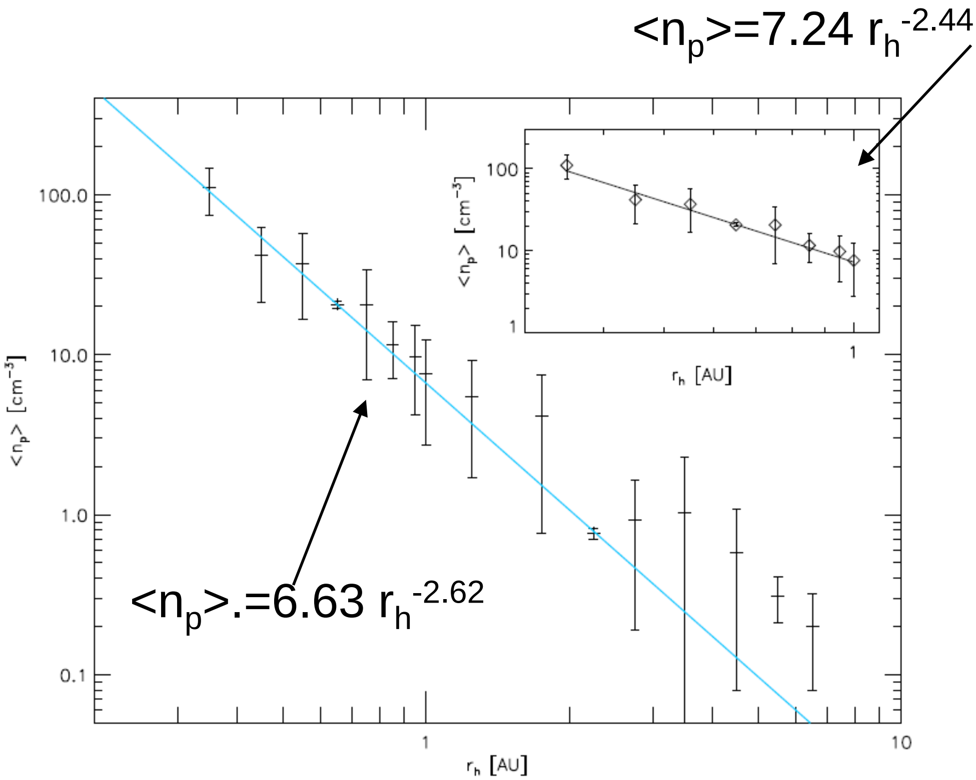
$$\langle B_0\rangle = (18.8 \pm 1.4)\ r_h^{-1.30 \pm 0.09}$$

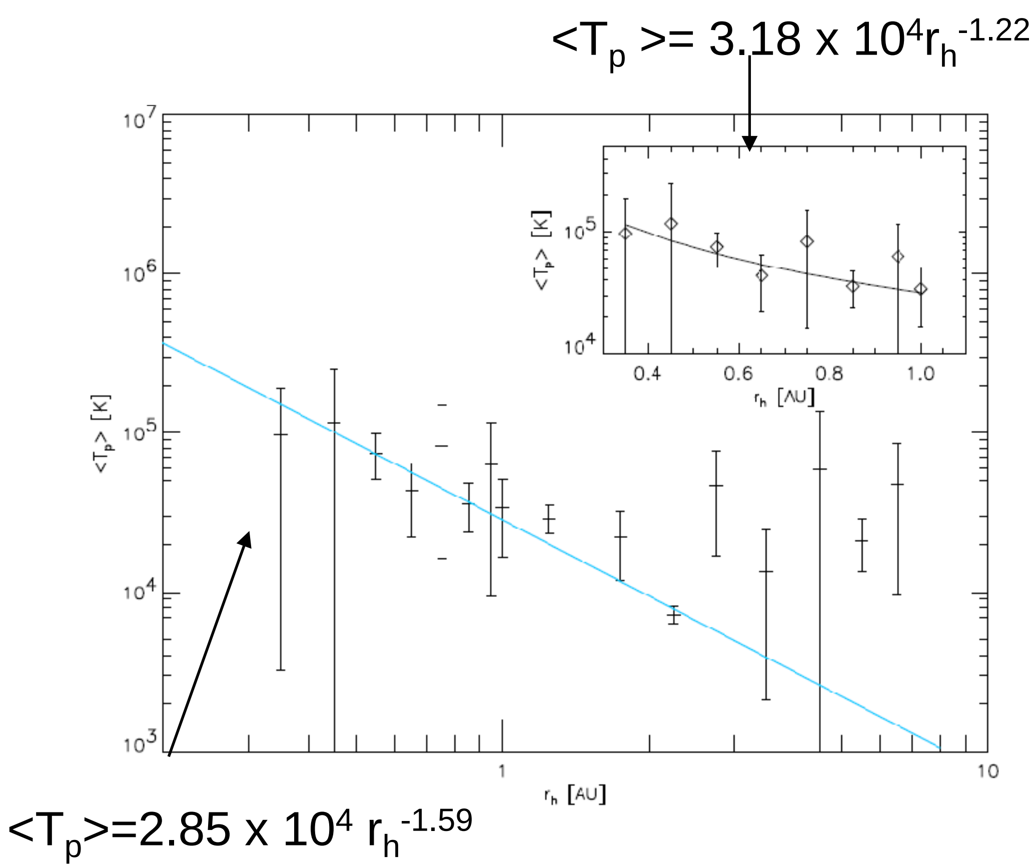
$$\langle B_0\rangle = (18.1 \pm 3.8)\ r_h^{-1.64 \pm 0.04}$$

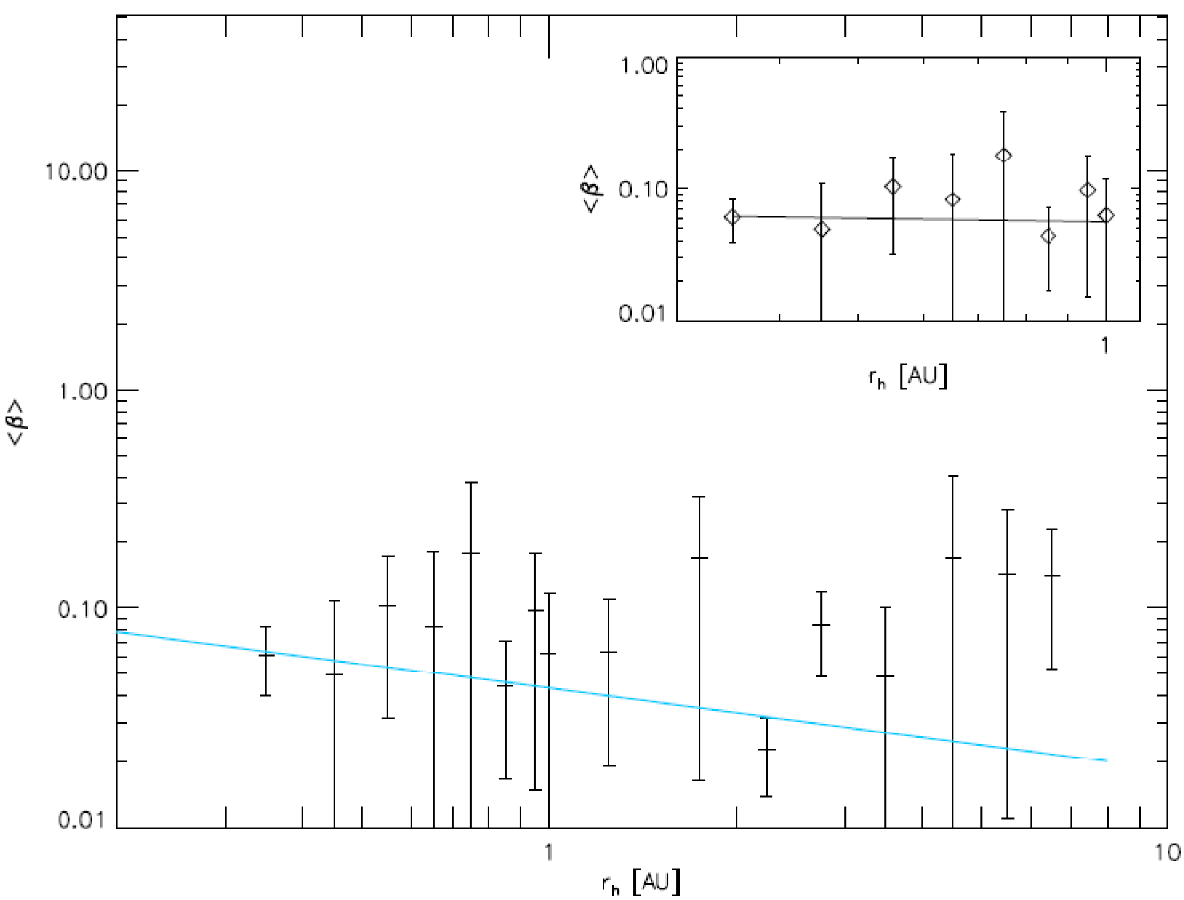


$$\langle D\rangle = (0.20 \pm 0.02)\ r_h^{0.61 \pm 0.09}$$

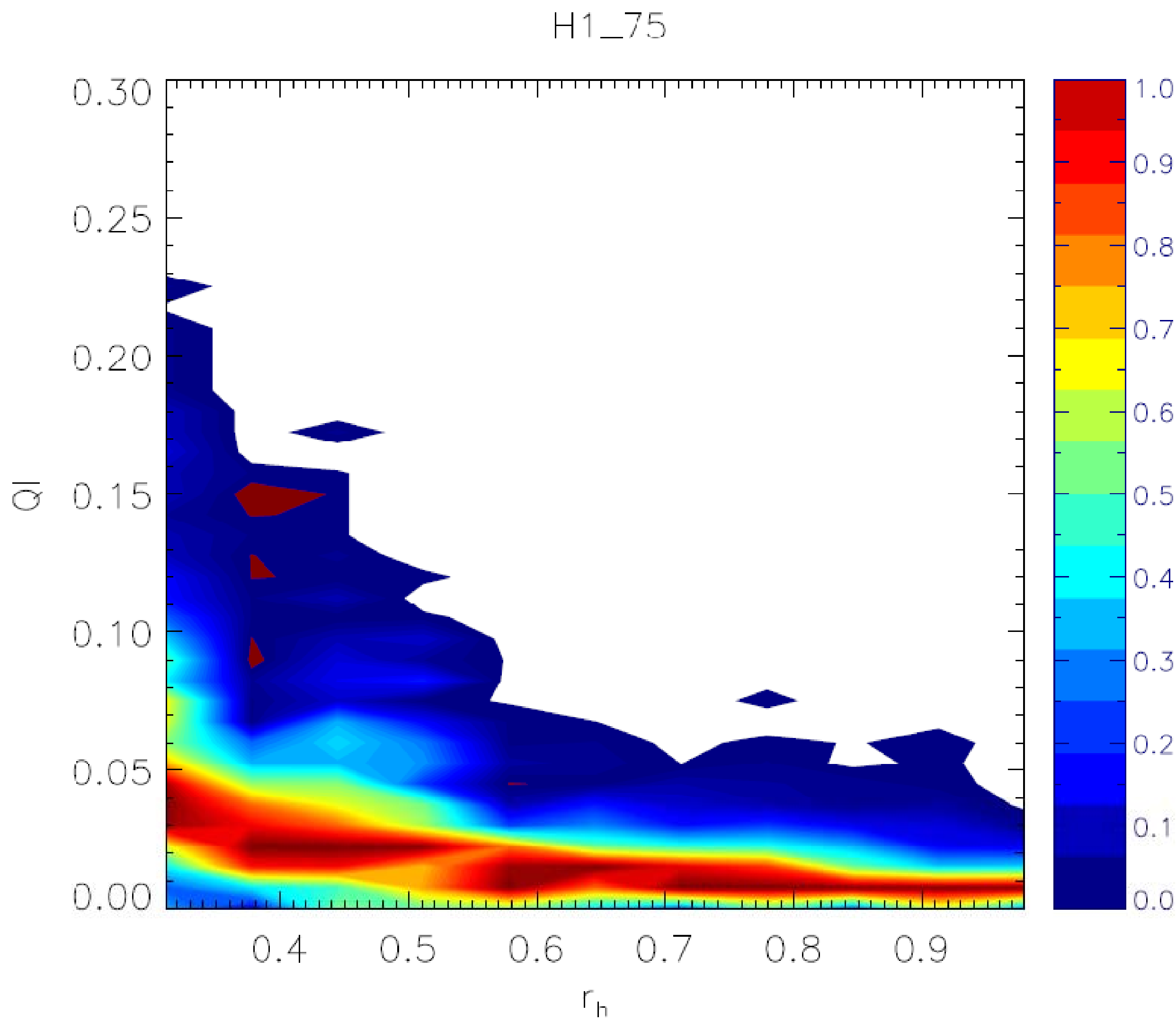
$$\langle D\rangle = (0.23 \pm 0.05) r_h^{1.14 \pm 0.44}$$


$\langle n_p \rangle = 7.24\, r_h^{-2.44}$
$\langle n_p \rangle . = 6.63\, r_h^{-2.62}$
$\langle n_p \rangle$ [cm^{-3}]
r_h [AU]
100.0
10.0
1.0
0.1
1
10
100
10
1

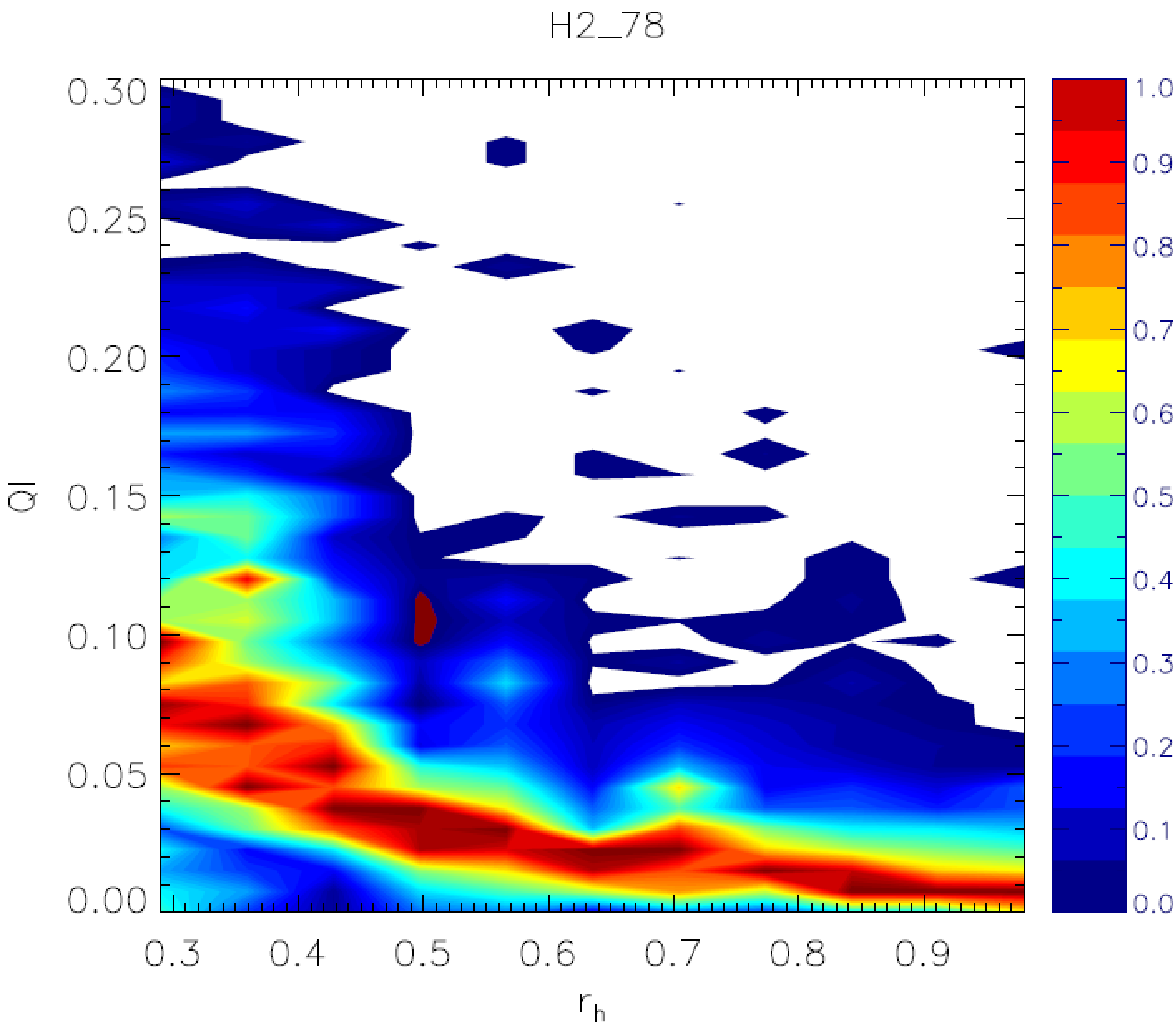

$\langle T_p \rangle = 3.18 \times 10^4 r_h^{-1.22}$
$\langle T_p \rangle = 2.85 \times 10^4\, r_h^{-1.59}$
$\langle T_p \rangle$ [K]
r_h [AU]
10^7
10^6
10^5
10^4
10^3
1
10
0.4
0.6
0.8
1.0



1.00
0.10
0.01
<β>
1
r_h [AU]
10.00
1.00
0.10
0.01
<β>
1
10
r_h [AU]

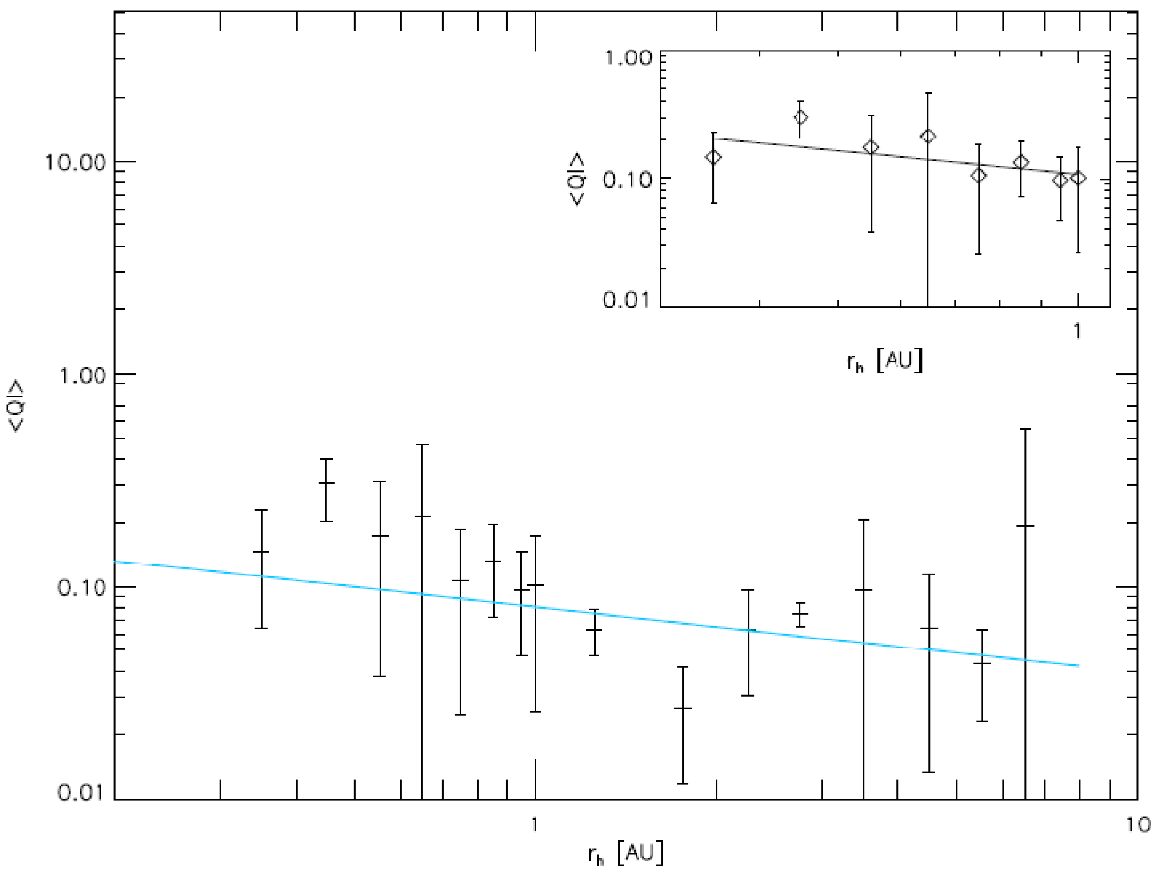


H1_75
0.30
0.25
0.20
0.15
0.10
0.05
0.00
QI
0.4
0.5
0.6
0.7
0.8
0.9
r_h
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0



H2_78
Ql
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.3
0.4
0.5
0.6
0.7
0.8
0.9
r_h
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

$$\langle QI\rangle = 0.11\, r_h^{-0.68}$$

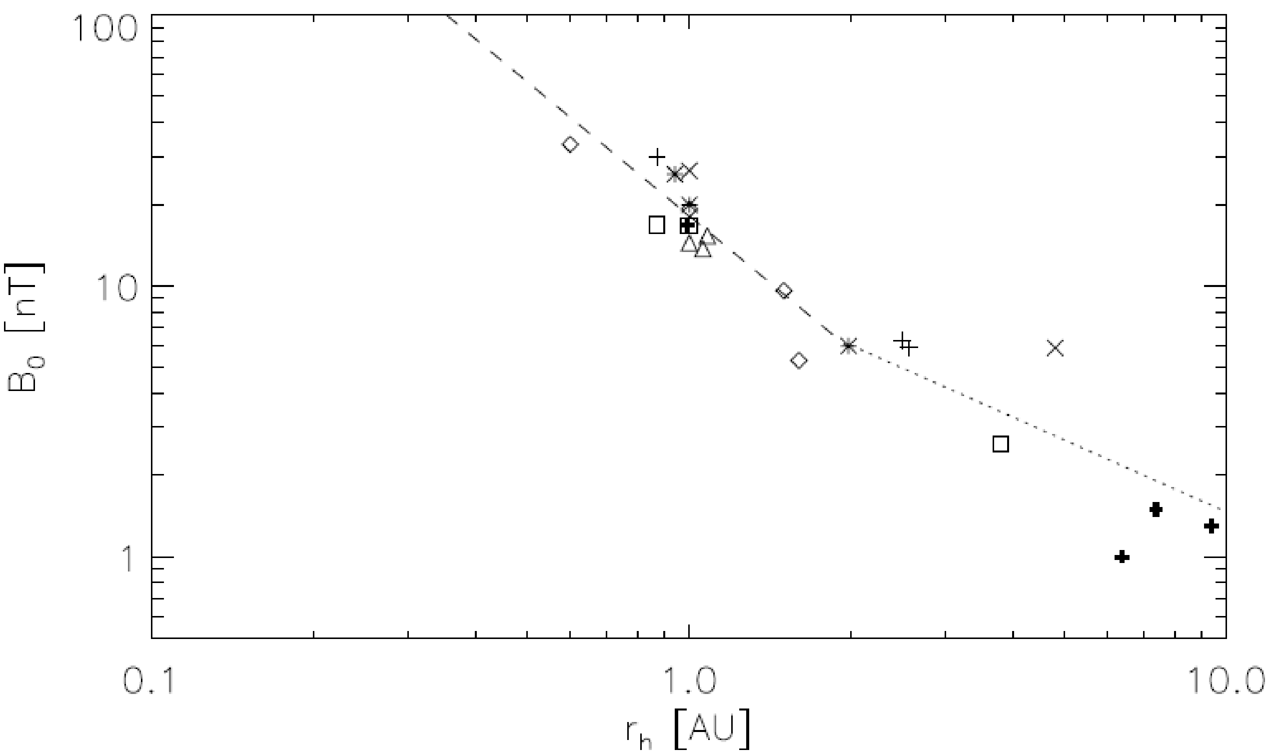


$$\langle QI\rangle = 0.08\, r_h^{-0.31}$$

Contrast: solar wind (1976):

$QI = 0.02\, r_h^{-1.14}$ (Helios1)

Approach 2: Spacecraft Lineups



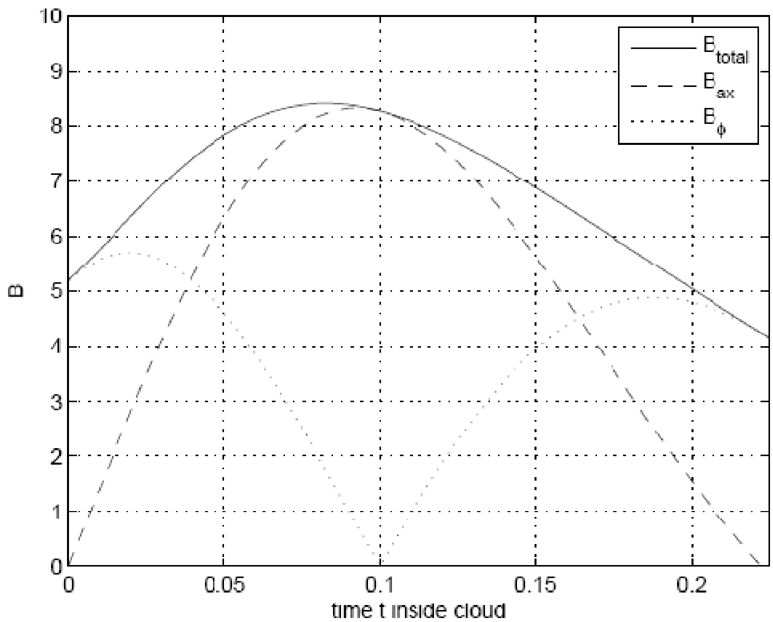
Approach 3: Freely expanding Lundquist Tube

$$B_{ax} = (B_0/\tau^2)J_0(\alpha r/\tau)$$

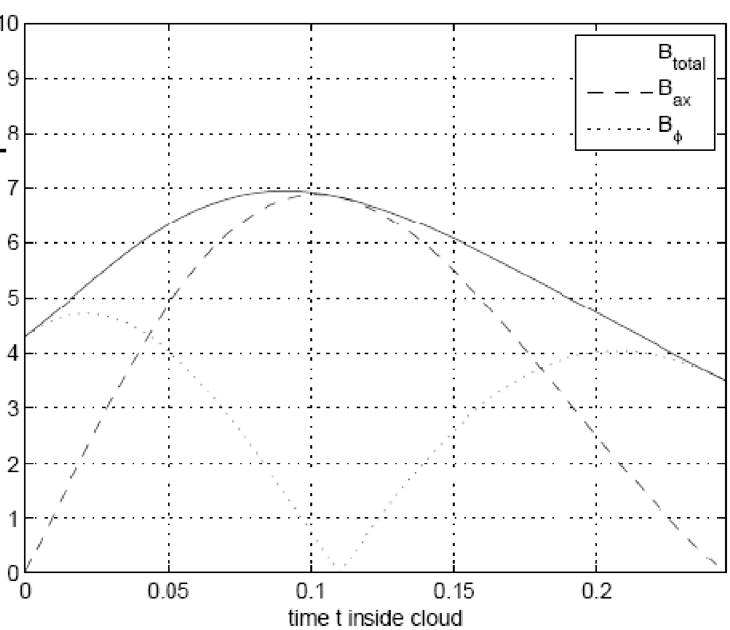
$$B_\phi = (B_0/\tau)J_1(\alpha r/\tau)$$

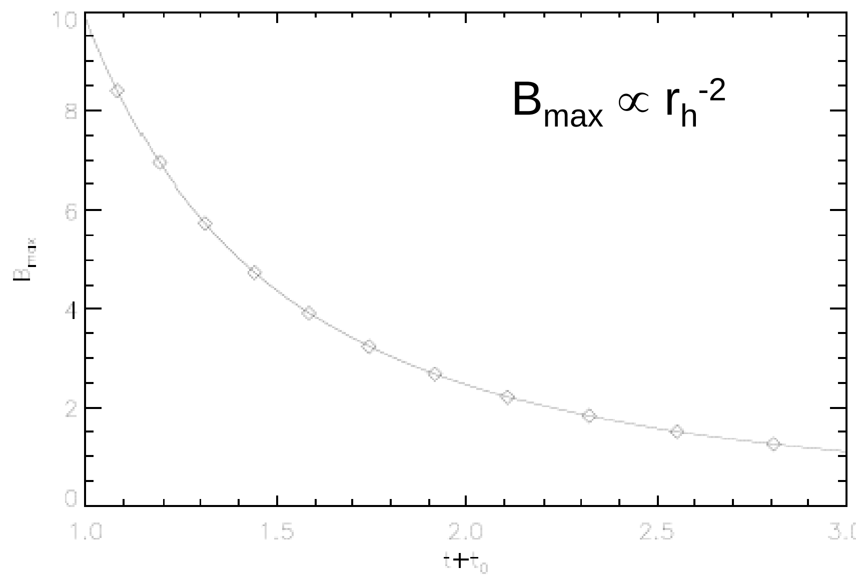
$\tau = (t+t_o)/t_o$ to: time from expulsion to start of observations at r_h

Observer x

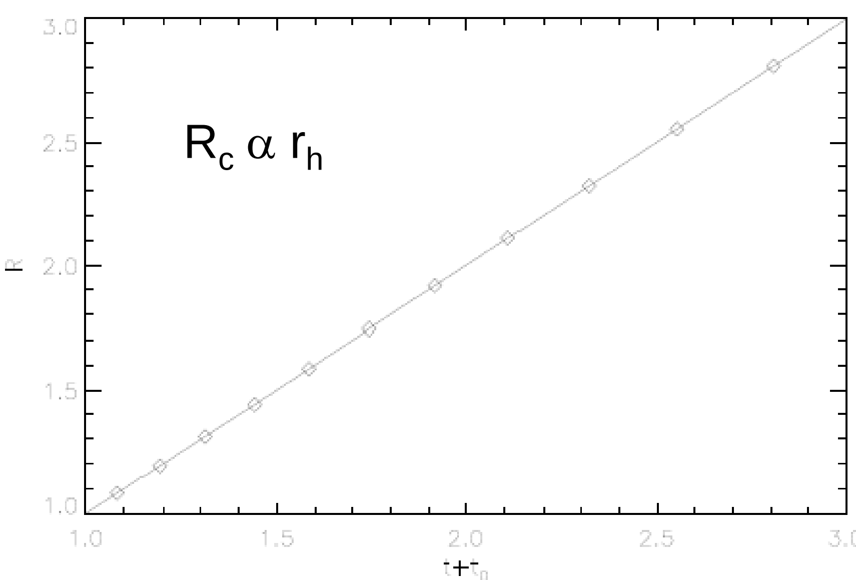


Observer x+1





$B_{max} \propto r_h^{-2}$
B_{max}
$t+\tau_0$



R_c α r_h
R
$t+\tau_0$

Conclusions

- Inner Heliosphere: modeled variation of the average central axial field strength: $< B_0 > [nT] = 18.1 r_h^{-1.64}$ [AU]; average diameter: $< D > [AU] = 0.23 r_h^{1.14}$.

- Useful for space weather predictions because they tell us *how parameters of these geoeffective configurations scale with* r_h, an essential input to, for example, "coupling functions" such as the ϵ parameter (*Perreault and Akasofu*, 1978). Coupling functions seek to express the fraction of solar wind energy and momentum tapped by the magnetosphere.

- In our data set, pertaining to the minimum and ascending phases of the solar cycle, the orientation of the axis of the underlying magnetic flux tube is generally found to lie along the east-west direction and in the ecliptic plane at all values of r_h. *But there is considerable scatter.*

- QI-index: $< QI >= 0.107 r_h^{-0.68}$. (i) Decreases with r_h; (ii) Solar wind has a more rapid decrease with r_h.

- The results from spacecraft alignments are in broad agreement with the statistics reported under approach 1.

- Predictions of freely-expanding Lundquist tube: $< D > \sim r_h$, broadly similar to that obtained in approach 1, while $< B_0 > \sim r_h^{-2}$, a stronger dependence than that obtained in approach 1.

- The results useful for 3-Dim studies of inner-heliospheric evolution of MCs.