# On the Radial Evolution of Magnetic Clouds

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**Abstract:** Magnetic clouds (MCs) are characterized as intervals of enhanced, smoothly rotating interplanetary magnetic field, low plasma beta and temperature in spacecraft in situ data and can be part of interplanetary coronal mass ejections (ICMEs). In this study we analyze the radial evolution of MCs using a sample of events detected by radial aligned spacecrafts at different heliocentric distances. The data-sets are fitted with a force-free, constant-$\alpha$ flux rope model. Using the outcome of this fitting model we calculate the estimated cross section diameter (assuming a cylindrical flux tube), the poloidal and the axial magnetic field and the electrical current. All these parameters are further studied as a function of heliocentric distance. Strong variations of the electrical current could be a indication of magnetic reconnection between the MC and the solar wind.

## Introduction

When an ICME propagates through the interplanetary medium, it is not independent from the surrounding area. In particular, it is influenced by the drag-force due to the solar wind, which results either in a deceleration or an acceleration of the ICME structure, depending on the relative speed between the ICME and the ambient solar wind. Moreover, the interior structure of an ICME, the magnetic flux rope, can interact with the interplanetary magnetic field by magnetic reconnection, where the topology of magnetic field lines is rearranged and magnetic energy is converted into thermal and kinetic energy. Magnetic reconnection observed in the Earth's magnetic field has already been associated with ICMEs (Farrugia et al., 2001) and analyzed in several studies. The interaction of ICMEs with different solar wind structures, even with the quiet solar wind, is an important topic in order to better understand their propagation behavior. Furthermore, reconnection of their interior magnetic structures with the solar wind can affect their geoeffectiveness.

## Data and Methods

We use an already existing data set of MCs, detected by more than one spacecraft at different heliocentric distances (e.g. *Helios 1* and *2*, *Pioneer 11*, *Vojager 1* and *2*), between 1974 and 1980 (see Leitner et al., 2007, Table 1.). The data are mainly analyzed by least-square fitting to a force-free, constant-$\alpha$ flux rope model (Burlaga, 1988; Lepping, Burlaga, and Jones, 1990). This model assumes a force-free magnetic field and a cylindrical geometry. The outcome of this fitting method is the magnetic field strength in the center of the cloud ($B_0$), the latitude ($\theta$) and longitude ($\Phi$) of the MC axis, the impact parameter ($p$), and the helicity ($H$). The estimated radius of the cloud ($r$) and the fitting outcome are used for calculating the electrical current ($I$):

$$I = \frac{2 r \pi}{\mu} B_{\varphi} ,$$

where $B_\varphi$ is the poloidal magnetic field. The current is further studied as a function of heliocentric distance. Strong variations of the current within MCs along their way could be a hint of magnetic reconnection between the MC and the solar wind.

## Results

For calculating the MC diameter we use the impact parameter ($p$), determined by the fitting model described above. This parameter is the closest distance of the spacecraft to the axis of the cloud. In combination with the orientation of the cloud it is possible to derive the diamter ($D$) of the MC. Figure 1 shows the evolution of the MC-diameter as a function of distance from the Sun for the analyzed event sample.

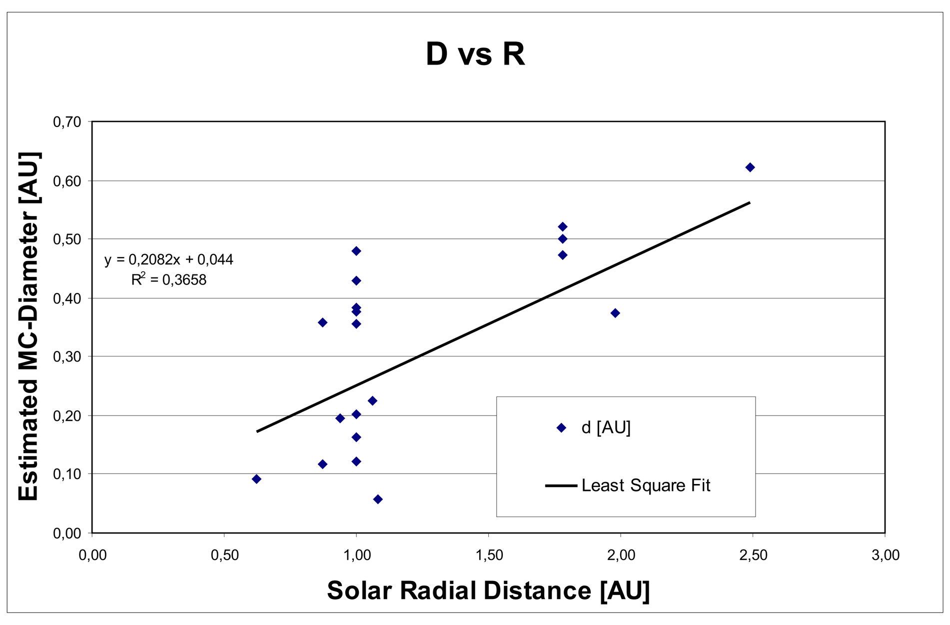


**Figure 1.** Estimated MC-diameter as a function of heliocentric distance. In principal MCs seem to expand with the distance to their origin. This sample is going to be expanded in order to get a broader data set.

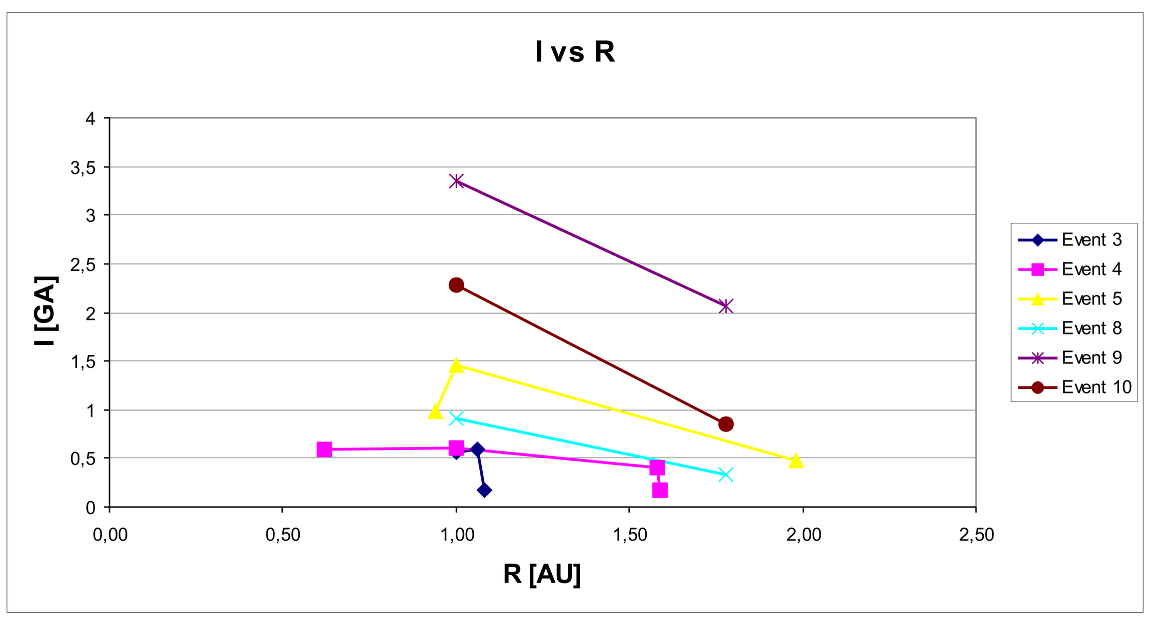


**Figure 2.** Electrical current as a function of heliocentric distance for 6 different events. Each event was measured at different positions in space at least two times. Event 5 (yellow) shows not the expected behavior, i.e. magnetic reconnection could have happened.

The calculation of the MC-diameter yields the radius of the MC cross section. This is needed to calculate the electrical current ($I$). We use the evolution of $I$ during the propagation of the MC as indicator for magnetic reconnection with the interplanetary magnetic field. It is assumed that $I \sim 1/R$. If $I$ is not decreasing with distance, this could be a hint of magnetic reconnection! Figure 2 shows the electrical current for 6 MCs, measured at 16 different positions in space, as a function of distance from the Sun. In the case of event 5 (yellow) reconnection could have happened between the first and the second measurement point.

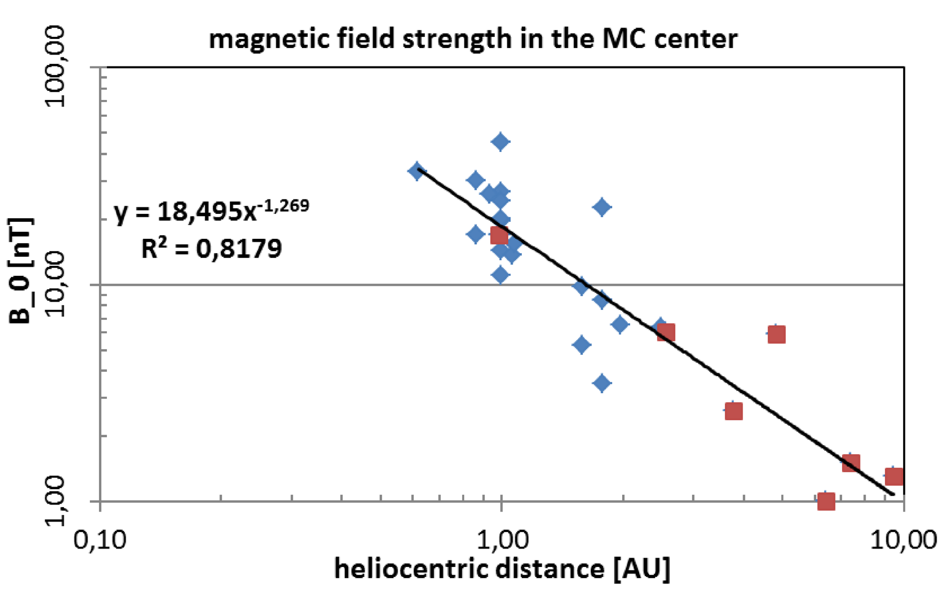


**Figure 3.** Magnetic field strength in the center of the MC as a function of radial distance from the Sun (double logarithmic scale). The straight line is a power law fit.

**Table 1.** MC parameters of the reconnection event found. The first six columns give the event number and the s/c positions in GSE coordinates. $B_0$, $\Phi$, $\theta$, $H$, and $p$ are the fitting outcome. $B_{tot}$ is the total magnetic field strength and $D$ is the estimated diameter of the structure.

| No. | s/c | doy | $r_h$[AU] | long | lat | $B_0$[nT] | $\Phi$[°] | $\theta$[°] | p | H | $B_{tot}$[nT] | D[AU] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5a | H2 | 4-5 | 0.94 | 98.9 | 0.0 | 25.86 | -22.6 | 12.9 | 0.47 | 1 | 18.75 | 0.195 |
| 5b | OMNI2 | 4-5 | 1.00 | 104.6 | 0.0 | 19.94 | -61.2 | -16.4 | 0.15 | 1 | 14.40 | 0.376 |
| 5c | V1 | 6-7 | 1.98 | 78.8 | 1.0 | 6.46 | -52.5 | 30.8 | 0.05 | 1 | 4.97 | 0.374 |

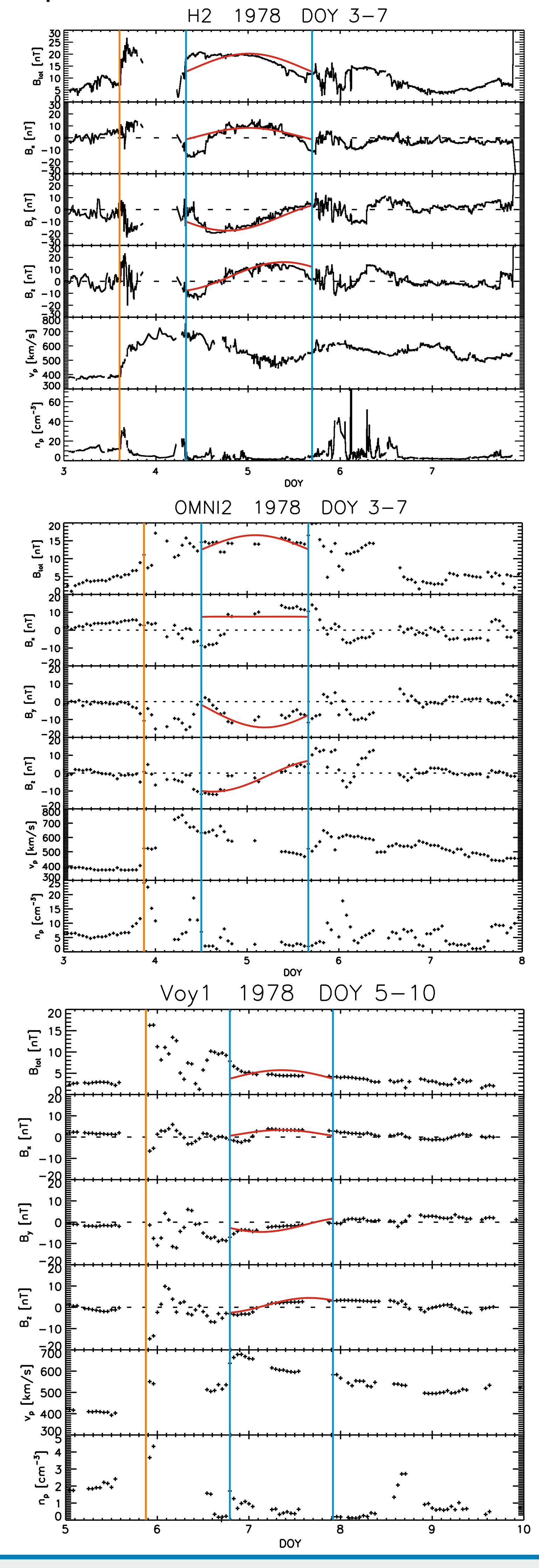


**Figure 4.** In situ measurements of all three s/c of the event showing a current increase. The yellow vertical lines mark the shock, the blue lines the MC borders. The red lines are the force-free fits of the magnetic field.

## Conclusions and Outlook

We analyzed a sample of 6 MCs, measured at different heliocentric distances. In one case the electrical current was not decreasing with distance, as expected. This could be an evidence for magnetic reconnection of the MC with the interplanetary magnetic field. This sample of multipoint measured MCs is going to be complimented by more recent events. Of interest is also the magnetic flux, the inductance and the magnetic field energy. The interaction of MCs with the interplanetary magnetic field is of big interest in order to enhance existing forecasting methods of possible geoeffective events.

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