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# Statistics of magnetic energies in solar active regions of different Hale and McIntosh classes

I. Zimovets and I. Sharykin

Space Research Institute of the Russian Academy of Sciences, 84/32, Profsoyuznaya str., Moscow, 117997 Russia

**Abstract.** A statistical analysis of the magnetic energies (of the nonlinear force-free and potential fields, $E_{\rm NLFFF}$, $E_{\rm POTF}$, and their difference – a proxy for the free magnetic energy, $E_{\rm FREE}$) in active regions (ARs) on the Sun of different Hale and McIintosh classes for the period from May 1, 2010 to 12 June, 2024 ($\approx$ 1.3 solar cycles) is presented. The magnetic field in ARs is calculated using the GX Simulator based on the photospheric vector magnetograms by the Helioseismic and Magnetic Imager (HMI) anboard the Solar Dynamics Observatory (SDO) and information about ARs contained in the daily Solar Region Summary (SRS) files provided by the NOAA SWPC. Distributions of different parameters have been determined in total for all ARs and separately for each Hale and McIntosh class, the mean values of the parameters and standard deviations were calculated for each class. As expected, it is found that the magnetic energies, unsigned magnetic flux, as well as the integral number of sunspots, the number of active regions, and the area of sunspots, integrated over ARs visible per day on the solar disk, exhibit an $\approx$ 11-year cyclicity. On average, magnetic energies of ARs increase with increasing Hale and McIntosh class (with sub-peaks in $E_{\rm POTF}$ and $E_{\rm NLFFF}$ for Hhx, Hkx, Cho–Cki), while the average fraction of the free magnetic energy, $E_{\rm FREE}/E_{\rm NLFFF}$ in ARs of different classes differs weakly. Correlation between $E_{\rm POTF}$ and $E_{\rm NLFFF}$ is almost identical for ARs of different Hale classes with the high values of the linear Pearson correlation coefficient, *ccp*, from 0.96 to 0.99. $E_{\rm FREE}$ is less correlated with $E_{\rm POTF}$ and $E_{\rm NLFFF}$ (*ccp* is from 0.32 to 0.71).

**Keywords:** Sun: activity, magnetic fields, sunspots, flares

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# 1 Introduction

Active regions (ARs) are places where the brightest phenomena of solar activity occur, including such potentially geoeffective ones as flares and CMEs (e.g., Toriumi & Wang 2019). ARs are inextricably linked with sunspots. The main source of energy in ARs is the magnetic field.

The two most famous classifications of ARs are the Hale magnetic classification (5 classes: $\alpha$, $\beta$, $\beta\gamma$, $\beta\delta$, $\beta\gamma\delta$) and the McIntosh morphological classification (60 classes of the Zpc type).

The purpose of this work is to collect statistics of magnetic energies in ARs for 2010–2024, in particular, to determine average values and standard deviations of magnetic energies in ARs of various Hale and McIntosh classes.

# 2 Data and Methods

Information about ARs is taken from the daily SRS files[1], namely: NOAA AR number, heliographic coordinates, Carrington longitude, sunspot group area ($A_{\rm SS}$), longitude size ($L_{\rm L}$), sunspot number ($N_{\rm SS}$), McIntosh and Hale classes.

Full-disk photospheric vector magnetograms of the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory, SDO, (Scherrer et al. 2012) were used as boundary data for extrapolations. We used magnetograms around 01:00 UT for each day, which is close to the time of SRS files (00:30 UT).

Extrapolation of the magnetic field was made in approximations of potential (POTF) and nonlinear force-free fields (NLFFF) using GX Simulator (Nita et al. 2023). Cartesian coordinate system with a step of 1500 km (at $L_{\rm L} \leq 12°$) or 3000 km (at $L_{\rm L} > 12°$) was used. The size of the calculation area along X-axis (longitude) was $L_{\rm x} = k_{\rm x} \times L_{\rm L}$, along Y-axis (latitude) $L_{\rm y} = k_{\rm y} \times L_{\rm L}$, and along the Z-axis was equal to the larger of $L_{\rm x}$ and $L_{\rm y}$, $k_{\rm x}$ and $k_{\rm y}$ ranged from 2.4 to 12 depending on $L_{\rm L}$.

Magnetic energies $E_{\rm POTF}$ and $E_{\rm NLFFF}$ were calculated as integrals over the computational 3D boxes of each ARs as $E = \int \left(\mathbf{B}^2/8\pi\right) dV$, except 10% of voxels near the side and top boundaries. The proxy of the free magnetic energy was calculated as $E_{\rm FREE} = E_{\rm NLFFF} - E_{\rm POTF}$. Also, we calculated the total unsigned magnetic flux, $\int |B_z\,(x, y, z = 0)|\, dS$ (see Zimovets & Sharykin 2024, for details).

Calculations were made for ARs in the central part of the solar disk (within ±70°) for the interval from May 1, 2010 to June 12, 2024. A total of 5144 SRS files were used. NOAA AR numbers for this interval varied from 11064 to 13711, i.e., 2647 different ARs. A total of 13414 data cubes were obtained.

[1] ftp://ftp.swpc.noaa.gov/pub/warehouse

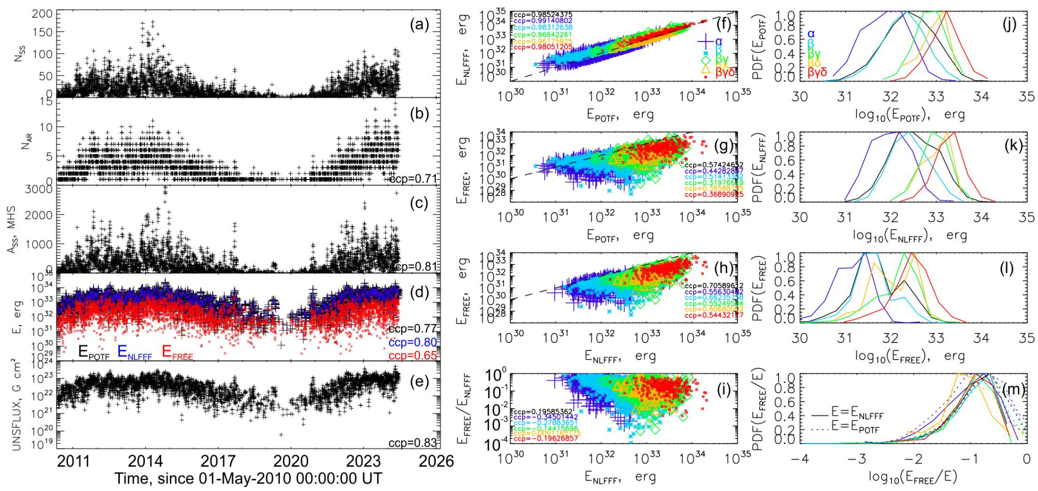


**Fig. 1.** (Left) Temporal behavior of parameters integrated over ARs on the solar disk with 1-day step from May 2010 to June 2024. (Middle) Paired dependences of magnetic energies in ARs of different Hale classes (f–h) and fraction of the free to total magnetic energy (j). (Right) Distributions of these parameters.

Temporal profiles of total sunspot number, number of ARs, sunspot area, magnetic energies, and unsigned magnetic flux integrated over ARs in 1-day step for the considered time interval are shown in Fig. 1(a–e). As expected, all parameters are subject to variations of the solar activity cyclicity. The parameters correlate with the sunspot number, with the linear Pearson correlation coefficient, *ccp*, ranging from 0.65 to 0.83.

For further analysis, we left only “isolated” ARs satisfying the following criteria: 1) imbalances of the magnetic flux and vertical current are less than 20%, 2) $E_{\mathrm{FREE}} > 0$. This leaves 5299 data cubes, among which 509 ARs of $\alpha$ class, 3525 of $\beta$, 839 of $\beta\gamma$, 97 of $\beta\delta$, and 329 of $\beta\gamma\delta$ classes. ARs of 57 McIntosh classes are present, except for three rare classes Esc, Fro, and Fri.

# 3 Results

## 3.1 ARs of Hale classes

Distributions of $E_{\mathrm{POTF}}$, $E_{\mathrm{NLFFF}}$, $E_{\mathrm{FREE}}$, and $E_{\mathrm{FREE}}/E_{\mathrm{NLFFF}}$, for Hale ARs are shown in Fig. 1(f–m). One can see: 1) on average, magnetic energies increase with increasing Hale class, 2) while the average fraction of free magnetic energy in ARs of different Hale classes differs weakly, 3) $E_{\mathrm{FREE}}$ in $\beta\delta$ ARs has two maxima, the left one is close to the maximum of the distributions for the lower classes $\alpha$, $\beta$, $\beta\gamma$ and the right

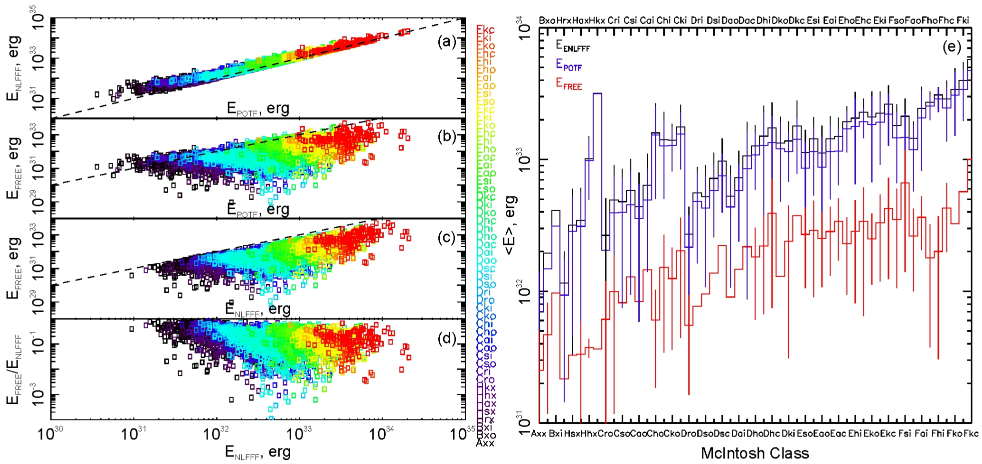


**Fig. 2.** Paired dependences of the magnetic energies in ARs of different McIntosh classes (a–c) and of $E_{\rm FREE}/E_{\rm NLFFF}$ (d). (e) Average magnetic energies ($E_{\rm NLFFF}$ – black, $E_{\rm POTF}$ – blue, $E_{\rm FREE}$ – red) in ARs of various McIntosh classes. Standard deviations are shown as vertical bars.

one is close to the maximum for the highest class $\beta\gamma\delta$, 4) there is high correlation between $E_{\rm NLFFF}$ and $E_{\rm POTF}$, *ccp* is almost identical for ARs of different classes (from 0.96 to 0.99), 5) $E_{\rm FREE}$ is weakly correlated with $E_{\rm POTF}$ and $E_{\rm NLFFF}$ (*ccp* from 0.32 to 0.71).

### 3.2 ARs of McIntosh classes

Distributions of $E_{\rm POTF}$, $E_{\rm NLFFF}$, $E_{\rm FREE}$, and $E_{\rm FREE}/E_{\rm NLFFF}$ for ARs of McIntosh classes are shown in Fig. 2(a–d), and the average values with standard deviations of $E_{\rm POTF}$, $E_{\rm NLFFF}$, and $E_{\rm FREE}$ are shown in Fig. 2(e). It can be seen: 1) on average, the magnetic energies of ARs increases with increasing McIntosh class, from small simple Axx to larger more complex *Fkc* class, 2) there are intermediate peaks of $E_{\rm POTF}$ and $E_{\rm NLFFF}$ for Hhx, Hkx, Cho–Cki classes without pronounced peaks in $E_{\rm FREE}$, 3) there is no clear dependence of $E_{\rm FREE}/E_{\rm NLFFF}$ with McIntosh class.

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