Solar-Terrestrial Physics. 2025, vol. 11, iss. 3, pp. 31–36 DOI: 10.12737/stp-113202504. © 2025 G.A. Makarov. Published by INFRA-M Academic Publishing House

DOI: 10.12737/stp-113202504

Received February 28, 2025
Accepted May 13, 2025

INFLUENCE OF INTERPLANETARY PARAMETERS ON THE DEGREE OF SYMMETRY OF THE RING CURRENT

G.A. Makarov
Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy SB RAS, Yakutsk, Russia, gmakarov@ikfia.ysn.ru

Abstract. The paper studies the influence of interplanetary factors on the degree of symmetry of the magnetospheric ring current. The geomagnetic indices *SYM-H*, *ASY-H,* and interplanetary parameters for the period 1981–2015 are considered. The indicator of the degree of symmetry of the ring current is the ratio *SYM-H*/*ASY-H*. Analysis is based on annual averages of geomagnetic and interplanetary parameters. This approach allows us to identify large-scale patterns. The relationships are examined of the degree of symmetry of the ring current and the indices *SYM-H* and *ASY-H* with the value B of the interplanetary magnetic field (IMF), the IMF north-south component B_n, and the solar wind velocity V. It is concluded that properties of magnetospheric ring currents are described by these indices more adequately when offsets in their values are taken into account than without regard for them. It is found that when offsets in *ASY-H* are considered the symmetric ring current prevails approximately twice over the asymmetric one for average conditions in the solar wind: V<550 km/s, B<10 nT, $|B_n|$<2 nT. Under quiet solar wind conditions (V<450 km/s, B<5.5 nT, $|B_n|$<0.7 nT), the degree of symmetry of the ring current increases. It is established that with intensification of interplanetary parameters (V, B, $|B_n|$) the symmetric ring current index *SYM-H* grows more strongly than the asymmetric ring current index *ASY-H*.

Keywords: geomagnetic indices *SYM-H* and *ASY-H*, magnetospheric ring current, interplanetary parameters.

INTRODUCTION

The magnetospheric ring current consists of two main parts: symmetric and asymmetric. The geomagnetic indices *SYM* and *ASY* were developed to estimate the symmetric and asymmetric ring current components respectively [Iyemori et al., 1992].

Quite a lot of works have studied the influence of interplanetary parameters on the *SYM* and *ASY* indices. Shi et al. [2006] have found that when the interplanetary magnetic field (IMF) north-south component B_n is negative, an increase in the solar wind (SW) dynamic pressure additionally enhances the ring current asymmetry. Singh et al. [2013] have examined the effect of smooth and abrupt changes in IMF B_n on *ASY-H* and *ASY-D* during magnetic substorms. Haiducek et al. [2017], using the SWMF system, have modelled the forecast of the geomagnetic indices K_p, *SYM-H*, *AL* and have established that the model excels at predicting *SYM-H*. Bhaskar and Vichare [2019] with the aid of an artificial neural network have successfully predicted *SYM-H* and *ASY-H* during nine geomagnetic storms of solar cycle 24; the SW velocity and density, as well as IMF B, B_y, B_z were utilized as input data. During the main phase of severe storms, there are noticeable deviations of the predicted index values from the observed ones, which indicates the effect of internal factors such as magnetospheric processes. In [Makarov, 2022] based on extensive statistical data, the relationships of *SYM-H* and *ASY-H* with key interplanetary parameters have been analyzed and it has been obtained that the dependence of *ASY-H* and *SYM-H* on the IMF north-south component is determined by the IMF strength. Moreover, it has been found that *SYM-H* and *ASY-H* depend on the SW plasma parameter β: their absolute values decrease with increasing β regardless of the sign of IMF B_n [Makarov, 2024]. It is assumed that this is due to the transition of the magnetosphere to quiet state because of the increasing predominance of thermal pressure over magnetic pressure in SW and a decrease in the level of turbulence.

Correlation relationships between *ASY-H* and interplanetary medium parameters for 107 magnetic storms with Dst<–50 nT induced by SW streams of different types (CIR — corotating interaction regions and ICME — interplanetary coronal mass ejections) have been investigated in [Boroev, Vasiliev, 2020] and it has been found that average *ASY-H* during the magnetic storm main phase depends on the electric field and the IMF southward component regardless of the stream type; no relationship between *ASY-H* and SW velocity has been detected. Namuun et al. [2023] have examined correlation relationships between *SYM-H* and various interplanetary parameters for 131 CME-driven magnetic storms and 161 CIR-induced magnetic storms. The authors have concluded that *SYM-H* in the case of CME storms has a greater dependence on the SW velocity and the convective electric field, and in the case of CIR storms it more strongly depends on the SW electric field, the velocity of the open magnetic flux $d\varphi/dt$, and the reconnection electric field E_{KL}.

Symmetric and asymmetric ring currents have different properties [Bakhmina, Kalegaev, 2008]. The symmetric ring current is formed due to decoupled motion of magnetospheric plasma protons and electrons, trapped by the geomagnetic field along closed trajectories around Earth, and it exists constantly. The partial ring current is formed in the night and dusk sectors near the geomagnetic equator due to enhanced magnetospheric convection during disturbances. The partial ring current is thought to develop during the magnetic storm main phase and to decay immediately after its maximum [Barkhatov et al., 2008]. Although the weak longitude asymmetry of the magnetospheric magnetic field measured on Earth's surface is also present during geomagnetically quiet periods, it is not known for certain whether it is related to the existence of the partial ring current in the quiet magnetosphere [Kalegaev et al., 2008].

Weygand and McPherron [2006] have studied such a characteristic of ring currents as the degree of symmetry, defined as the *SYM-H*/*ASY-H* ratio. They have figured out that the ring current is always asymmetric. Examining *SYM* and *ASY* variations, the authors [Weygand, McPherron, 2006; Iyemori et al., 2010] have revealed that there are offsets of their values. According to the definition given in these papers, offset is a nonzero index value under magnetically quiet conditions. Weygand and McPherron [2006] have suggested that the offsets may be caused by the joint effect of various magnetospheric current systems. Earlier in [Alexeev et al., 1996; Maltsev et al., 1996; Tsyganenko, Sitnov, 2005], it has been shown that not only the ring current itself, but also magnetopause currents, the magnetotail, and field-aligned currents contribute to geomagnetic characteristics of the ring current.

Most works on the relationship of *SYM* and *ASY* with interplanetary parameters have been performed for storm and sub-storm conditions. The study of solar-terrestrial relations and space weather phenomena is incomplete without taking into account the large-scale properties of the ring current and its long-term dynamics. Such properties can be investigated by analyzing data with a time resolution of a day or longer. Such studies are often conducted by statistical methods using daily and annual average terrestrial, interplanetary, and solar parameters. For daily average terrestrial parameters, different phases of geomagnetic storms may overlap; therefore, the storm parameters (phase, intensity, duration, etc.) will largely be smoothed over. In this regard, it is important to study variations in annual average *SYM* and *ASY* obtained from daily average data. The purpose of the work is to examine the effect of interplanetary parameters on the degree of magnetospheric ring current symmetry.

EXPERIMENTAL DATA

The *SYM* and *ASY* indices are calculated from the *H* and *D* components of the geomagnetic field at six mid-latitude stations (the network consists of more than ten stations). These indices have a 1-min time resolution and are divided into *SYM-H*, *SYM-D*, *ASY-H*, and *ASY-D*. *SYM-H* and *SYM-D* are, in fact, averaged deviations of the geomagnetic field *H* and *D* components from the quiet level at observation stations adjusted for geomagnetic latitude, whereas *ASY-H* and *ASY-D* are defined as the differences between maximum and minimum *H* and *D* components after subtracting the corresponding symmetric parts from the disturbance field. The *SYM-H* index is generally negative (similar to *Dst*), *SYM-D* takes values of both signs, and *ASY-H* and *ASY-D* are always positive. The method for determining the *SYM* and *ASY* indices is described in detail in [Iyemori et al., 2010].

The data is analyzed based on annual average *SYM-H* and *ASY-H* and interplanetary parameters for 1981–2015. The geomagnetic indices were taken from the website of the World Data Center for Geomagnetism [https://wdc.kugi.kyoto-u.ac.jp/index.html]; interplanetary data, from the website of NASA's Space Physics Data Facility [http://omniweb.gsfc.nasa.gov/]. The IMF components in this database are represented in the RTN coordinate system: the R-axis is directed radially from the Sun; the T- axis, toward the Sun's rotation; and the N-axis is the vector product of the R and T axes. At zero heliographic latitude, the N and T axes are parallel. The RTN and GSE coordinate systems at near-Earth distances differ in the opposite directions of the R and X axes, as well as T and Y axes respectively.

After excluding days with no data on interplanetary and geomagnetic parameters, 10759 days remained in the data array. When examining the relationship of *SYM-H* and *ASY-H* with the IMF north-south component B_n, the data was classified according to the sign of B_n: there were 5670 days with $B_n<0$ (including 118 days when daily average B_n was zero), and 5089 days with $B_n>0$.

RESULTS AND DISCUSSION

Figure 1 plots the index of the degree of ring current symmetry *SYM-H*/*ASY-H* as function of IMF *B*, SW velocity *V*, and IMF north-south component B_n (*c*). The plots yielded the corresponding linear regression equations and correlation coefficients *r*. The index of the degree of symmetry is seen to depend on *B* and *V*; the correlation coefficient between *SYM-H*/*ASY-H* and IMF *B* is 0.8; and between *SYM-H*/*ASY-H* and *V*, it does not exceed 0.5. As for the relationship between *SYM-H*/*ASY-H* and IMF B_n, when considering the data regardless of the sign of the IMF north-south component (panel (*c*)) it is absent: $r = 0.1$. Since the IMF north-south component is one of the main factors influencing magnetospheric processes, the index data was divided into two subarrays according to the sign of B_n. Panel (*d*) shows the relationships between *SYM-H*/*ASY-H* and B_n separately for southward and northward IMF. The relationship is seen to be pronounced: at $B_n \leq 0$, r=0.73; at $B_n > 0$, r=0.50. It can be said that as the absolute values of the interplanetary parameters increase, the value of *SYM-H*/*ASY-H* increases in absolute value and approaches 1.

SYM-H/*ASY-H*=–1 means that the symmetric and asymmetric components of the ring current are equated to the maximum values of the interplanetary parameters. It turns out that the asymmetric current prevails over the

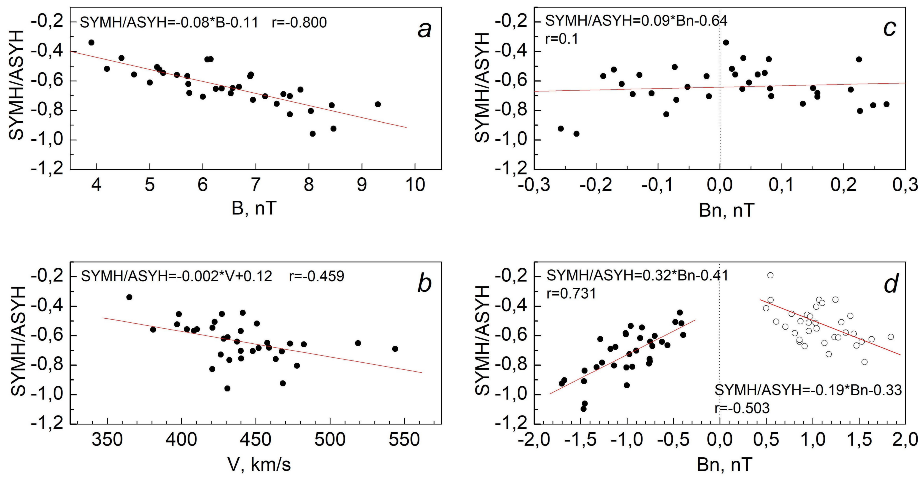

Figure 1. Index of the degree of ring current symmetry *SYM-H*/*ASY-H* as function of IMF *B* (*a*), solar wind velocity *V* (*b*), and IMF north-south component B_n without classifying (*c*) and by classifying (*d*) data according to the sign of B_n; panels present linear regression equations and correlation coefficients *r*

symmetric one most of the time, but this cannot be the case. With large-scale averages, it is logical to assume that the symmetric component of the ring current should dominate the asymmetric one due to the fact that in the absence of geomagnetic disturbances the symmetric ring current is constantly present in the magnetosphere [Kalegaev et al., 2008]. Such a current decays slowly during the geomagnetic storm recovery phase, which can last quite a long time [Weygand, McPherron, 2006], whereas the asymmetric ring current develops during the geomagnetic storm main phase and its decay time is much shorter [Weygand, McPherron, 2006; Bakhmina, Kalegaev, 2008].

In Introduction, offsets of *SYM* and *ASY* were discussed. Weygand and McPherron [2006] have suggested that the offset of *SYM-H* probably occurs due to the combination of three effects: Chapman—Ferraro currents under quiet conditions; ring current under quiet conditions, and the difference between the tail effect on quiet and stormy days, whereas the offset of *ASY-H* is due to the combination of two effects: the asymmetric ring current that is always present in the inner magnetosphere, and noise on local time plots, which was caused by incomplete subtraction of the quiet day variation at each station.

The presence of an offset in *Dst* values has been detected in [Takalo, Mursula, 2001; Hakkinen et al., 2003]. Takalo and Mursula [2001] have investigated the seasonal diurnal variations of the *Dst* index on quiet and all days and have found that these variations are associated with uneven distribution of stations of the *Dst* network. Analysis of diurnal and seasonal variations in *Dst* allowed Hakkinen et al. [2003] to conclude that stations of the *Dst* network had different entry levels so that average *Dst* differed by 10 nT. In [Makarov, 2020], it has been shown that the annual *Dst* variation occurs due to the uneven distribution of the network of stations involved in determining *Dst*.

In [Weygand, McPherron, 2006], the *SYM-H* index was adjusted for the contribution of SW dynamic pressure to it, and during statistical study on storm time it was estimated that the offset of *SYM-H* and *ASY* is ~18±2 nT depending on the method in use. Zhao et al. [2022], having examined the relationship of very large geomagnetic storms (Δ *SYM-H*<–200 nT) with SW parameters, came to the conclusion that the empirical formulas employed in such works estimate the intensity of storms with large statistical errors. In [Makarov, 2021] based on data on seasonal variations in the indices, as well as on the results of regression analysis of annual average indices and the level of magnetic activity for 1981–2016, it has been found that the offsets for *SYM-H* is –0.1 nT and for *ASY-H* is 13.6 nT. In this paper, it is difficult to take into account the offset during statistical study of the contribution of different sources to *SYM-H* and *ASY-H*.

Given the importance of the offsets of the indices considered, we re-estimate the relationship between the index of the degree of ring current symmetry and interplanetary parameters, using offsets obtained in [Makarov, 2021] from the results of statistical study. The offset of *SYM-H* is tiny, so it can be ignored, but in *ASY-H* it is significant. After *ASY-H* was corrected for 13.6 nT, *SYM-H*/*ASY-H* were calculated (for the results see Figure 2).

Comparing Figure 2 with Figure 1 shows that, firstly, there is practically no relationship between *SYM-H*/*ASY-H* and interplanetary parameters, except for the weak connection between the symmetry index and the IMF north-south component when the data was classified according to the sign of B_n (*d*); and, secondly, average *SYM-H*/*ASY-H* varies near –2. This behavior of the symmetry index may indicate the predominance of the symmetric ring current over the asymmetric one in the case of annual average data. Indeed, the symmetric ring current exists continuously, whereas the partial ring current develops during the magnetic storm main phase and decays immediately after its maximum. The ring current becomes

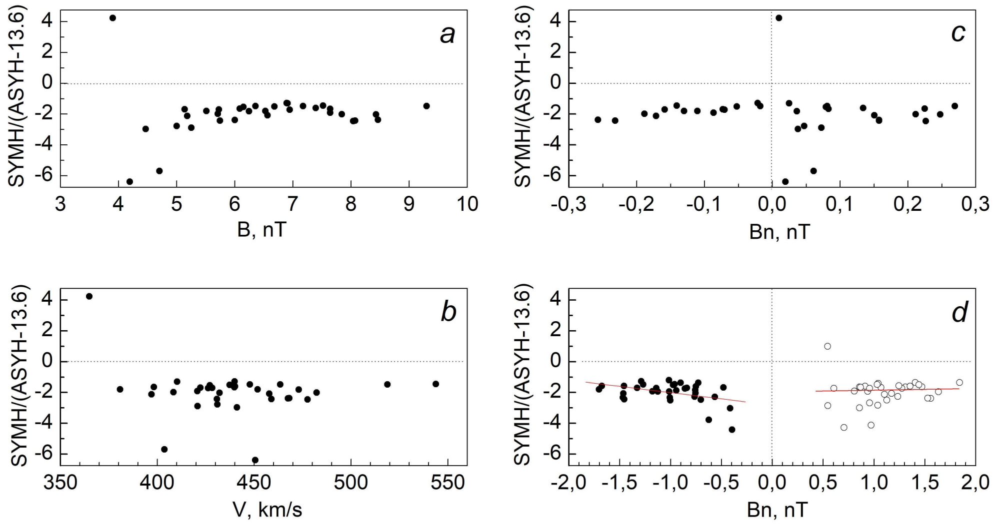

Figure 2. Index of the degree of ring current symmetry *SYM-H*/*ASY-H* as function of IMF*B* (*a*), SW *V* (*b*), and the IMF north-south component B_n (without classifying (*c*) and by classifying (*d*) data according to the sign of B_n) after considering the offset of *ASY-H*; panels exhibit linear regression equations and correlation coefficients *r*

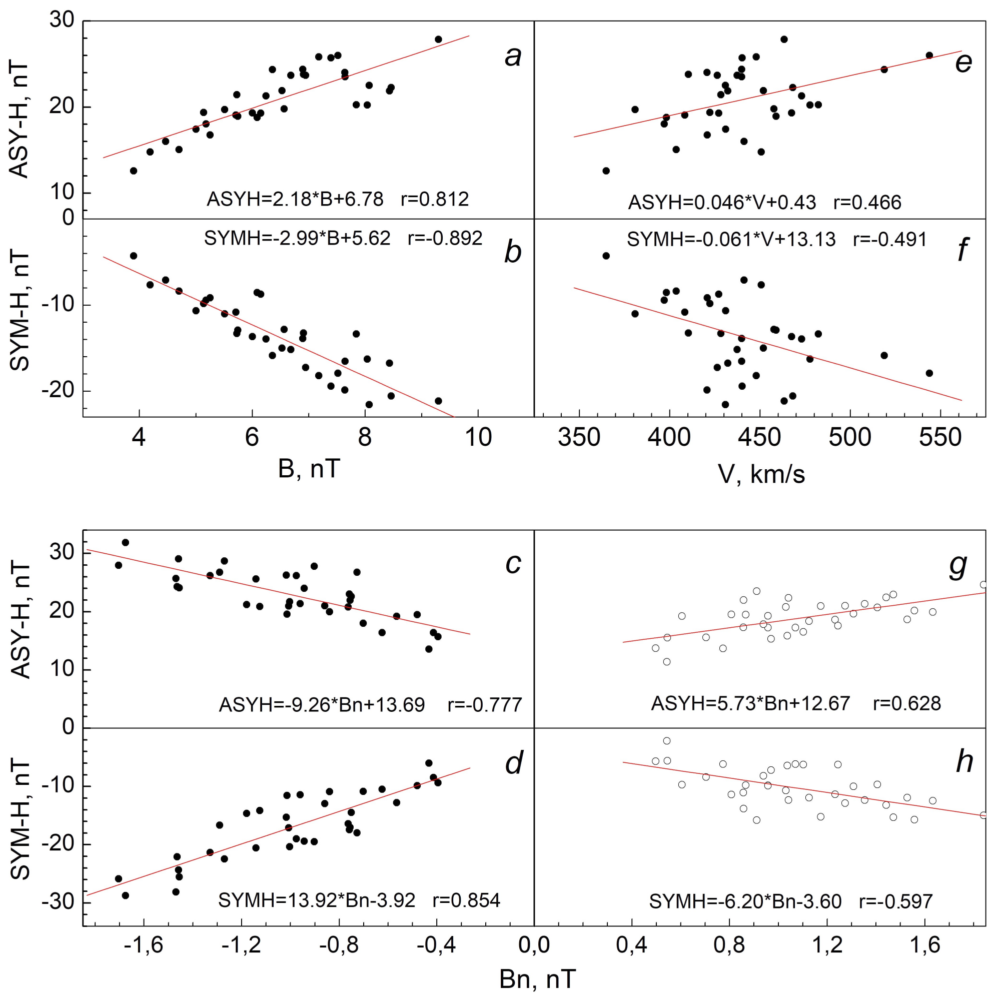

Figure 3. The *ASY-H* and *SYM-H* indices as function of IMF *B* (*a* and *b* respectively), SW velocity *V* (*e* and *f*), and the IMF north-south component B_n (*c*, *d*, *g*, *h*; data is classified according to the sign of B_n); panels show linear regression equations and correlation coefficients *r*

symmetric during the recovery phase [Kalegaev et al., 2008]. Since the storm recovery phase is much longer (about three times or more) than the main phase, the symmetric ring current persists for a longer time and at daily averaging makes a contribution to geomagnetic variations, which exceeds the contribution of the asymmetric ring current in the main phase when the intensity of this current is much higher. It is known [Weygand, McPherron, 2006], for example, that the response time for *SYM-H* (5.25 and 64.3 hr) is almost twice as long as that for *ASY-H* (2.2 and 20.9 hrs).

In Figure 2, *a*, *b*, *c*, three points can be seen when $|SYM\text{-}H/ASY\text{-}H|>4$, they correspond to small values of *B*, *V*, and $B_n>0$, i.e. to the cases when the partial ring current is minimum. The outlier with positive symmetry corresponds to positive *SYM-H*. Panel (*d*) quite clearly demonstrates the nonlinear relationship of *SYM-H*/*ASY-H* with B_n according to which the symmetric ring current noticeably prevails over the asymmetric current at small values of B_n. The index of the degree of ring current symmetry can be seen to increase when $V<450$ km/s, $B<5.5$ nT, $|B_n|<0.7$ nT. Such patterns are expected due to different properties of symmetric and asymmetric currents. Thus, when taking into account the offset, *ASY-H* more adequately reflects properties of magnetospheric ring currents than when ignoring it. The offsets of the indices are caused by contributions of all major magnetospheric current systems.

Figure 3 illustrates the correlation relationships of *ASY-H* and *SYM-H* with interplanetary parameters. When the relationship with B_n was examined, the data was divided into two subarrays: $B_n\le 0$ and $B_n>0$; in other cases, the sign of B_n was ignored. The relationships shown in the figure are consistent with the known ones — the geomagnetic indices increase in absolute value with increasing *B*, *V*, and $|B_n|$. Note should be made of the linear regression coefficients: in all equations related to interplanetary parameters, the coefficients for *SYM-H* are higher than for *ASY-H*, with values of both indices being comparable. This implies that *SYM-H* increases more strongly than *ASY-H* as the absolute values of SW parameters increase: 1.37 for *B*, 1.33 for *V*, 1.5 for $B_n<0$, and 1.08 for $B_n>0$. This paper is based on annual average data. With this averaging of data, storm and substorm processes are smoothed out; in addition, it is necessary to take into account time scales of ring current components — they are larger in the symmetric component [Weygand, McPherron, 2006]. The said *SYM-H* property probably also makes an additional contribution to the relationship of *SYM-H*/*ASY-H* with interplanetary parameters.

MAIN RESULTS

The geomagnetic index *ASY-H* has been shown to more accurately measure properties of magnetospheric ring currents when taking into account the offset of its values than when ignoring this offset. When considering the offset of *ASY-H*, the symmetric component of the ring current prevails approximately twice over the asymmetric one for average conditions in the solar wind: $V<550$ km/s, $B<10$ nT, $|B_n|<2$ nT. When the solar wind is quiet ($V<450$ km/s, $B<5.5$ nT, $|B_n|<0.7$ nT), the index of the degree of ring current symmetry increases.

From annual average *SYM-H* and *ASY-H*, it has been found that with an increase in the absolute values of interplanetary parameters (SW velocity, IMF magnitude IMF north-south component), the symmetric ring current index *SYM-H* increases more strongly than the asymmetric ring current index *ASY-H*.

The work was financially supported by the Government assignment (State Registration Number 122011700182-1).

REFERENCES

Alexeev I.I., Belenkaya E.S., Kalegaev V.V., Feldstein Y.I., Grafe A. Magnetic storms and magnetotail currents. *J. Geophys. Res*. 1996, vol. 101, no. A4, pp. 7737–7747. DOI: 10.1029/95JA03509.

Bakhmina K.Yu., Kalegaev V.V. Modeling the partial ring current effect in a disturbed magnetosphere. *Geomagnetism and Aeronomy*. 2008, vol. 48, no. 6, pp. 713–718.

Barkhatov N.A., Levitin A.E., Tserkovnyuk O.M. Relation of the indices characterizing the symmetric (*SYM*) and asymmetric (*ASY*) ring currents to the *AE* (*AU*, *AL*) indices of auroral electrojet activity. *Geomagnetism and Aeronomy*, 2008, vol. 48, no. 4, pp. 499–503.

Bhaskar A., Vichare G. Forecasting of *SYM-H* and *ASY-H* indices for geomagnetic storms of solar cycle 24 including St. Patricks day, 2015 storm using NARX neural network. *Journal of Space Weather and Space Climate.* 2019, vol. 9, no. A12. DOI: 10.1051/swsc/2019007.

Boroyev R.N., Vasiliev M.S. Relationship of the *ASY-H* index with interplanetary medium parameters and auroral activity in magnetic storm main phases during CIR and ICME events. *Sol.-Terr. Phys*. 2020, vol. 6, iss. 1, pp. 35–40. DOI: 10.12737/stp-61202004.

Haiducek J.D., Welling D.T., Ganushkina N.Y., Morley S.K., Dogacan Su Ozturk. SWMF global magnetosphere simulations of January 2005: Geomagnetic indices and cross-polar cap potential. *Space Weather.* 2017, vol. 15, pp. 1567–1587.

Hakkinen L.V.T., Pulkkinen T.I., Pirjola R.J., Nevanlinna H., Tanskanen E.I., Turner N.E. Seasonal and diurnal variation of geomagnetic activity: Revised *Dst* versus external drivers. *J. Geophys. Res*. 2003, vol. 108, no. A2, p. 1060. DOI: 10.1029/2002JA009428.

Iyemori T., Araki T., Kamei T., Takeda M. *Mid-latitude geomagnetic indices ASY and SYM (Provisional) No. 1: 1989–1990.* Data Analysis Center for Geomagnetism and Space Magnetism; Kyoto University, Japan, 1992, 240 p.

Iyemori T., Takeda M., Nose M., et al. *Mid-latitude geomagnetic indices ASY and SYM for 2009 (Provisional)*. Data Analysis Center for Geomagnetism and Space Magnetism; Kyoto University, Japan, 2010. URL: http://wdc.kugi.kyoto-u.ac.jp/aeasy/asy.pdf (accessed October 5, 2021).

Kalegaev V.V., Bakhmina K.Yu., Alexeev I.I., Belenkaya E.S., Feldstein Ya.I., Ganushkina N.V. Ring current asymmetry during a magnetic storm.*Geomagnetism and Aeronomy*. 2008, vol. 48, no. 6, pp. 747–759.

Makarov G.A. Geometric factor in seasonal variations of daily average values of the geomagnetic index *Dst*. *Sol.-Terr. Phys*. 2020, vol. 6, iss. 4, pp. 50–56. DOI: 10.12737/stp-64202008.

Makarov G.A. Offset in the geomagnetic indices of the magnetospheric ring current. *Sol.-Terr. Phys*. 2021, vol. 7, iss. 3, pp. 29–35. DOI: 10.12737/stp-73202103.

Makarov G.A. Geomagnetic indices *ASY-H* and *SYM-H* and their relation to interplanetary parameters. *Sol.-Terr. Phys*. 2022, vol. 8, iss. 4, pp. 36–43. DOI: 10.12737/stp-84202203.

Makarov G.A. Large-scale relationships of the geomagnetic indices *SYM-H* and *ASY-H* with the north-south IMF component and the solar wind beta parameter. *Sol.-Terr. Phys*. 2024, vol. 10, iss. 3, pp. 91–96. DOI: 10.12737/stp-103202411.

Maltsev Y.P., Arykov A.A., Belova E.G., Gvozdevsky B.B., Safargaleev V.V. Magnetic flux redistribution in the storm time magnetosphere. *J. Geophys. Res*. 1996, vol. 101, no. A4, pp. 7697–7704.

Namuun B., Tsegmed B., Li L.Y., Leghari G.M. Differences in the response to CME and CIR drivers of geomagnetic disturbances. *Sol.-Terr. Phys*. 2023, vol. 9, iss. 2, pp. 31–36. DOI: 10.12737/stp-92202304.

Shi Y., Zesta E., Lyons L.R., Yumoto K., Kitamura K. Statistical study of effect of solar wind dynamic pressure enhancements on dawn-to-dusk ring current asymmetry. *J. Geophys. Res*. 2006, vol. 111, A10216. DOI: 10.1029/2005JA011532.

Singh A.K., Sinha A.K., Pathan B.M., Rajaram R., Rawat R. Effect of prompt penetration on the low latitude *ASY* indices. *J. Atmos. Solar-Terr. Phys.* 2013, vol. 94, pp. 34–40.

Takalo J., Mursula K. A model for the diurnal universal time variation of the Dst index, *J. Geophys. Res*. 2001, vol. 106, no. A6, pp. 10905–10914.

Tsyganenko N.A., Sitnov M.I. Modeling the dynamics of the inner magnetosphere during strong geomagnetic storms. *J. Geophys. Res*. 2005, vol. 110, A03208. DOI: 10.1029/2004JA010798.

Weygand J.M., McPherron R.L. Dependence of ring current asymmetry on storm phase. *J. Geophys. Res.* 2006, vol. 111, A11221. DOI: 10.1029/2006JA011808.

Zhao M.X., Le G.M., Lu J.Y. Can we estimate the intensities of great geomagnetic storms (Δ*SYM-H*≤–200 nT) with the Burton equation or the O'Brien and McPherron equation? *Astrophys. J*. 2022, vol. 928, p. 18. DOI: 10.3847/1538-4357/ac50a8.

URL: https://wdc.kugi.kyoto-u.ac.jp/index.html (accessed March 29, 2025).

URL: http://omniweb.gsfc.nasa.gov/

The paper is based on material presented at the 20th Annual Conference on Plasma Physics in the Solar System, February 10–14, 2025, Space Research Institute of the Russian Academy of Sciences, Moscow, Russia.

Original Russian version: Makarov G.A., published in Solnechno-zemnaya fizika. 2025, vol. 11, no. 3, pp. 36–41. DOI: 10.12737/szf-113202504.

How to cite this article

Makarov G.A. Influence of interplanetary parameters on the degree of symmetry of the ring current. *Sol.-Terr. Phys*. 2025, vol. 11, iss. 3, pp. 31–36. DOI: 10.12737/stp-113202504.