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Ionospheric Sq Currents in the Mid and High Latitudes of Europe

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ABSTRACT **Original Research Article**

Magnetometer observations recorded in 2008 from geomagnetic stations deployed across Africa under the Magnetic Data Acquisition System (MAGDAS) were utilized to investigate the ionospheric solar quiet (Sq) current system at the mid- and high-latitude regions of Europe. To effectively distinguish between the internal and external magnetic field and current contributions associated with Sq variations, a spherical harmonic analysis (SHA) technique was employed. The results indicate that the Sq current system exhibits a pronounced dawn-to-dusk behavior. Notably, the external current variations differ markedly from the internal current components in both magnitude and phase characteristics. Seasonal analysis reveals that the external current attains its maximum intensity during the June solstice at the HRN and LER stations, while at the DOU station the peak occurs during the September equinox. The corresponding peak current strengths are approximately 4.0×10^3 A, 3.5×10^3 A, and 0.9×10^3 A, respectively.

Keywords: Ionospheric, Sq Currents, Latitudes.

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Introduction

At ground level, we may witness three distinct parts of the magnetic field: The three main components of Earth's magnetic field are the Main Field, which is thought to be generated by electrical currents in the fluid outer core of the planet, the External Magnetic Field, which is thought to be produced by interactions between the solar wind and the Earth's ionosphere, and the Crustal Field, which is associated with the magnetism of rocks in the crust. When the Earth's atmosphere experiences an electric current that fluctuates, it causes similar electric currents to flow in the conducting Earth below the current's source. The distribution of electrically conducting materials in the Earth and the properties of the source currents dictate the amplitude, direction, and penetration depth of the induced currents. Magnetometers at Earth's surface observatories track the combined exterior (source) and interior (induced) components of the fields produced by the currents. By dissecting these currents using integral methods like Spherical Harmonic Analysis (SHA), we can learn about the conductivity of the deep Earth from the amplitudes and phase connections (Chapman and Bartels, 1940). The source current's period of variation and the distribution of electrically conducting materials in the region begin studied determine the depth to which the generated current penetrates the deep earth. (Okeke and Obiekezie, 2010).

For a half-sector of the Earth that induced Australia, Campbell and Schiffmacher (1998) established analogous ionospheric source currents approximating the quiet-day geomagnetic variations. To account for the extraordinarily silent 1965 environment, they employed a spherical harmonic separation of the exterior and inside fields. Their research showed that the current system's monthly behavior pointed to a clockwise vortex source, with January showing a maximum of 12.8 x 104A and June showing a minimum of 4.4 x 104A. When solar activity is high, the Sq currents are approximately twice as strong as when it is low, as pointed out by Takeda (1999). Takeda (2002) demonstrated that solar activity is dependent on the Sq amplitude by comparing it to other values of conductivity for the same value. The seasonal change, he observed, appears to be caused either by variations in neutral winds or by the magnetic impact of the field-aligned current (FAC) that flows between the two hemispheres and is produced by the asymmetry in the dynamo action.

The objective of this study is to use the paired external and internal coefficient of the SHA to find the source current and induced courants, and then to disentangle the quiet-day field variations from the equatorial and low latitude regions of Africa into their respective external and internal field contributions.

Datasource

The geomagnetic dataset analyzed in this study consists of average hourly measurements collected during 2008 from selected geomagnetic observatories located within the study region. These observatories include Dourbes (50.1° N, 4.599° E), Hornsund (77.0° N, 15.55° E), and Lerwick (60.153° N, 1.1493° W). The data were acquired through geomagnetic stations installed under the Magnetic Data Acquisition System (MAGDAS) operated by Japan.

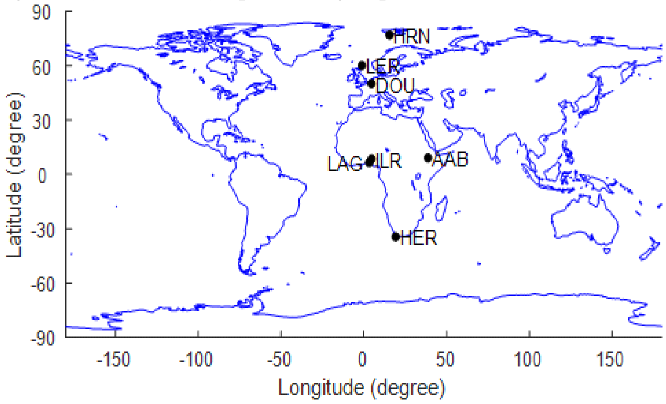


Fig 1. Geological map showing the study area

Method of Analysis

This study solves the magnetic potential function V using the Spherical Harmonic Analysis (SHA) method, which was developed by Guass in 1838. The two components of the potential function, the external (source) and the interior (induced) parts, were first demonstrated by Guass (1838). T is the sum of the internal (induced) current and the external source current as spherical harmonics, and he represented the magnetic potential of the Sq field, V, as a function of the daily mean values at universal time.

$$V_n^m = C + a \sum_{n=1}^{\alpha} \sum_{m=0}^{n} \left\{ \left({}_{an}^{me} \left(\frac{r}{a}\right)^n + {}_{an}^{mi} \left(\frac{a}{r}\right)^{n+1} \right) \cos(m\phi) + \left({}_{bn}^{me} \left(\frac{r}{a}\right)^n + {}_{bn}^{mi} \left(\frac{a}{r}\right)^{n+1} \right) \sin(m\phi) \right\} p_n^m(\theta) \quad (1)$$

Here, C, θ, a, r, and ϕrepresent the constant of integration, geomagnetic colatitude, Earth's radius, and the local time of the observatory, respectively. The coefficients ${}_n^{me}, a_n^{mi}, b_n^{me}$ $and\ b_n^{mi}$ correspond to the Legendre polynomial coefficients, where the superscripts $e$and $i$denote the external and internal components, respectively. The functions P_m^n are Legendre polynomials that depend solely on the colatitude θ. The integers $n$and $m$define the degree and order, respectively. Following Campbell (1997), the equivalent current function $J(\phi)$, expressed in amperes for a given hour of the day, where $\phi/15$represents the longitude divided by 15°, is derived as follows:

$$J = \sum_{m=1}^{4} \sum_{n=m}^{12} \left(U_n^m \cos\cos(m\phi) + V_n^m \sin\sin(m\phi) \right) P_n^m \quad (2)$$

In this formulation, the maximum value of the order $m$is set to 4, while the degree $n$is limited to a maximum value of 12. Under these constraints, the representation of the external current is expressed as follows:

$$U_n^m = -\left(\frac{5R}{2\pi}\right)\left(\frac{2n+1}{n+1}\right) a_n^{me} \left(\frac{a}{R}\right)^n \quad (3)$$

$$V_n^m = -\left(\frac{5R}{2\pi}\right)\left(\frac{2n+1}{n+1}\right) b_n^{me} \left(\frac{a}{R}\right)^n \quad (4)$$

And the internal current representation, we have:

$$U_n^m = -\left(\frac{5R}{2\pi}\right)\left(\frac{2n+1}{n}\right) a_n^{mi} \left(\frac{R}{a}\right)^{n+1} \quad (5)$$

$$V_n^m = -\left(\frac{5R}{2\pi}\right)\left(\frac{2n+1}{n}\right) b_n^{mi} \left(\frac{R}{a}\right)^{n+1} \quad (6)$$

Where, R is the radius of the Earth in kilometers.

The parameter a represents the radius of a hypothetical spherical surface on which an electric current may flow to reproduce, through spherical harmonic analysis (SHA), the magnetic fields observed at the Earth's surface. This conceptualization gives rise to the term *equivalent current*. The primary dynamo current sources are widely considered to be located within the ionospheric E-region, at an altitude of approximately 100 km. Given the substantial evidence supporting the E-region as the origin of these dynamo currents, the radius $a$is taken to be approximately equal to the Earth's radius R. Consequently, the ratio $\left[\frac{a}{R} - 1\right]$becomes negligibly small and may therefore be omitted from the current calculations (Campbell, 2003). Under this assumption, the intensity of the equivalent external current I, comprising the latitudinal component $\theta$and the longitudinal component ϕ, can be computed in amperes from the equivalent current function Jas follows:

$$I_\theta = \frac{1}{r\ sin\theta} \frac{\partial J}{\partial \phi} \quad (7)$$

$$I_\emptyset = -\frac{1}{r} \frac{\partial J}{\partial \emptyset} \quad (8)$$

Accordingly, the combined current intensity, incorporating both the internal and external components, may be expressed as follows:

$$I = I_\theta + I_\emptyset \quad (9)$$

Results and Discussion

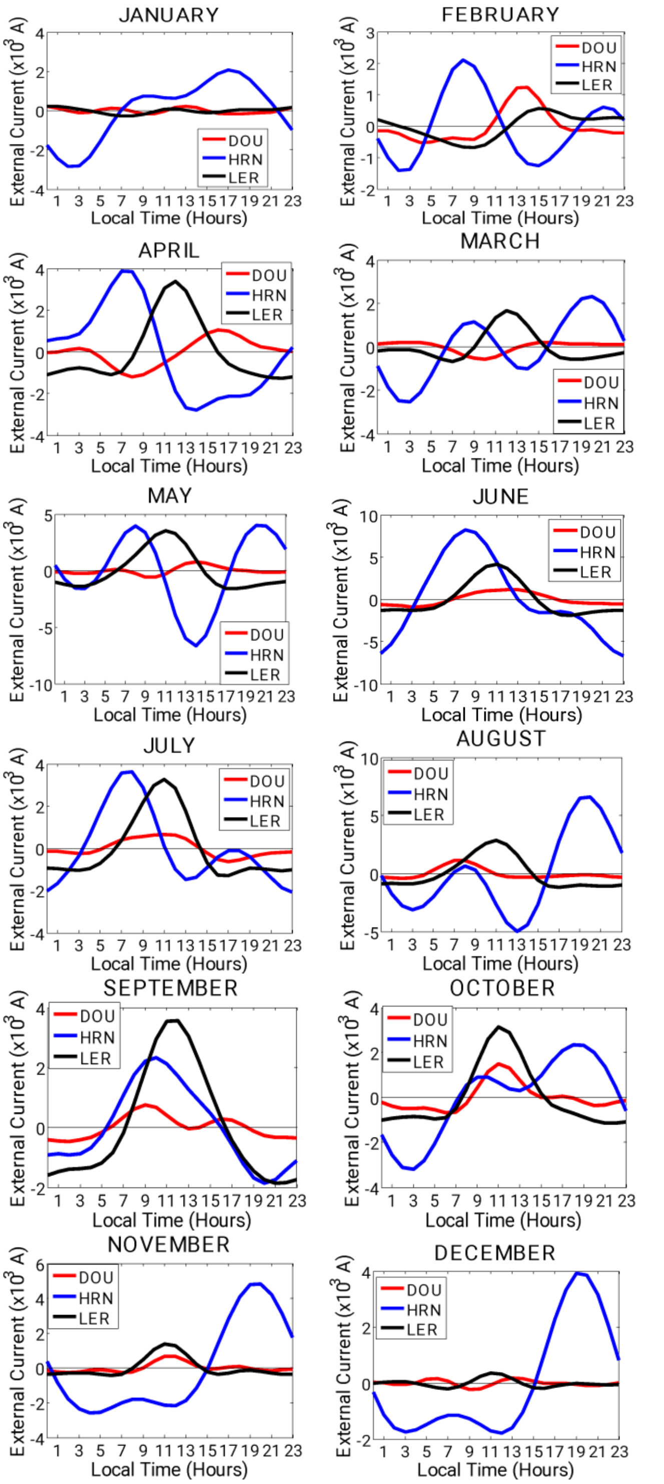
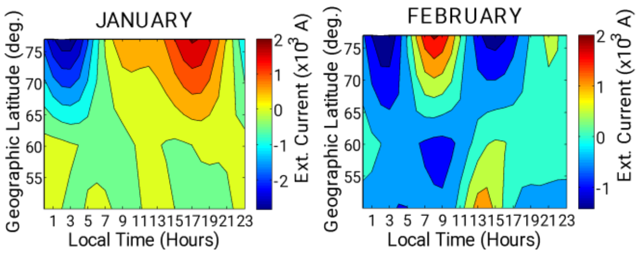


Fig 2. External Sq current across Europe (DOU, HRN and LER)



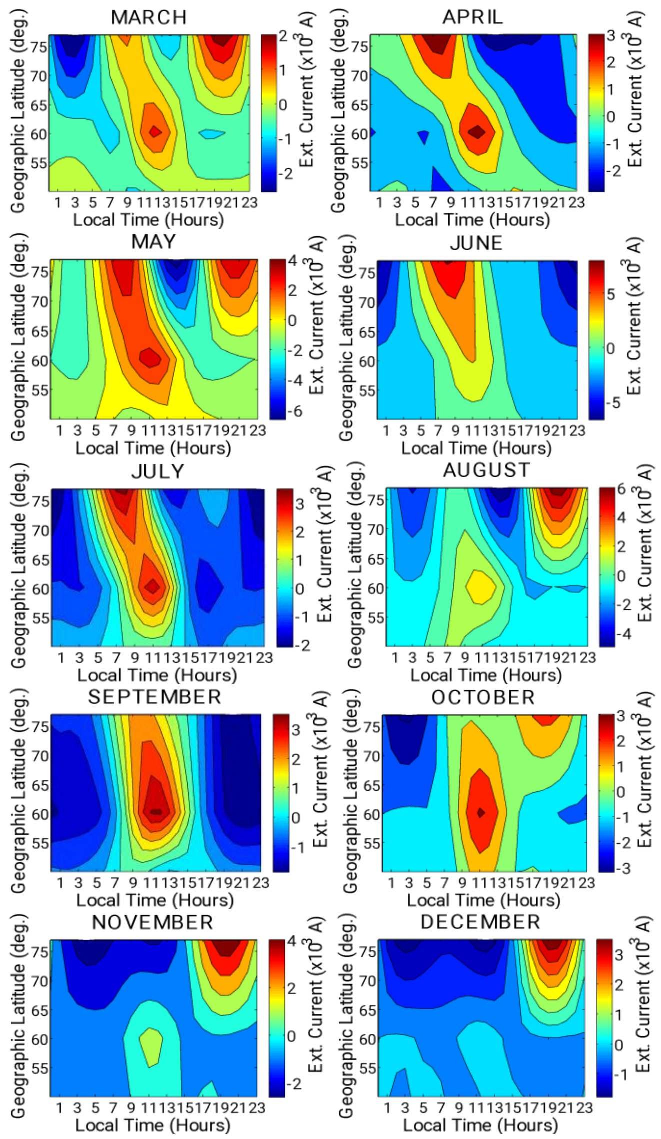


Fig 3. Contour map of External current for mid and high latitudes of Europe

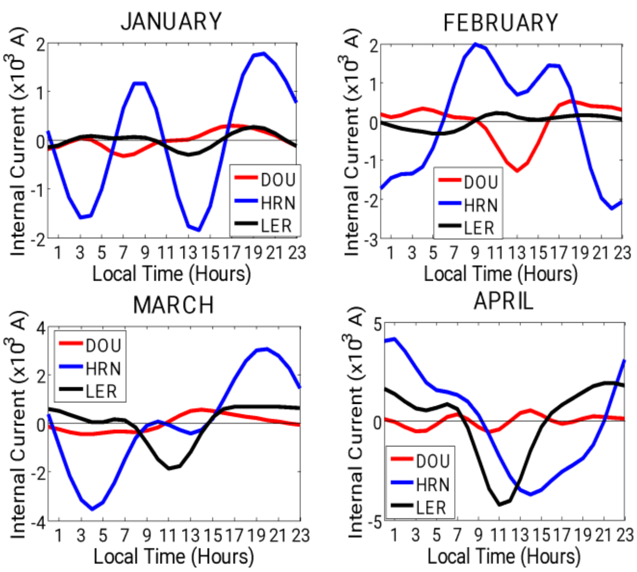
Figure 2 displays the DOU, HRN, and LER external current curves, and Figure 3 depicts the corresponding contour map for the three European stations. Throughout the day, from sunrise to sunset, the external currents varied. After a slow rise at midnight, the external current curves for DOU and LER reach their peak intensities between 11:00 and 15:00, and then they gradually fall back down to midnight levels. You can see the same thing happening with the external current contour maps. There appears to be a positive variation pattern, since the contour lines of the contour map are increasing inwards. The current variation in HRN is not regular.

Since the sun, the primary ionizer in the ionosphere, sets sail at night, the nighttime values are negligible. When solar activity is high, the Sq currents are approximately twice as strong as when it is low, as pointed out by Takeda (1999). The ionospheric ionization at any particular location is determined by the sun's absolute output and its position in the sky, as pointed out by Moldwin (2008).

Production due to photoionization stops when the amount of sunlight decreases to zero at night. On the other hand, we don't see zero currents, thus we can rule out ionospheric sources as the origin of the nighttime currents. Such currents originate from different places than magnetospheric and ring currents, as pointed out by Moldwin (2008). It was also noted by Obiekezie (2012) that these currents enter the ionosphere at night, even when the Earth's magnetic field is quiet. Other researchers, including Campbell (1979), Okeke and Rabiu (1998), Rabiu (2002), and Obiekezie et. al. (2013), have also documented these non-zero currents at night.

Throughout the day, from sunrise to sunset, the internal currents varied. There is a noticeable difference in the amplitude and phase of the internal current variation compared to the outward current variation. Variations in phase and amplitude are caused by variations in Earth's conductivity. Figure 5 shows that this is also mirrored in the internal current contour maps. Additionally, the HRN station displayed an atypical fluctuation in internal current. We find that the computed internal and exterior currents are smaller than what Campbell et al. (1993) and Obiekezie and Okeke (2010) had predicted.

Maximum external currents were observed in June solstice at HRN and LER and in September Equinox at DOU with a value of approximately 4.0×10^3A, 3.5×10^3A and 0.9×10^3A respectively. Maximum external current is expected in March or September equinox while a minimum is expected in December for the Northern stations and in June for the Southern stations. This is so because the sun is directly over the equator during the equinoctial months thus making ionization maximum in the equatorial ionosphere during these months. In June, the sun is in the Northern Hemisphere hence, ionization will be minimum in the Southern Stations and vice versa. The stations HRN and LER are at high latitudes in the Northern Hemisphere this explains why maximum ionospheric current is observed in June Solstice at those stations.



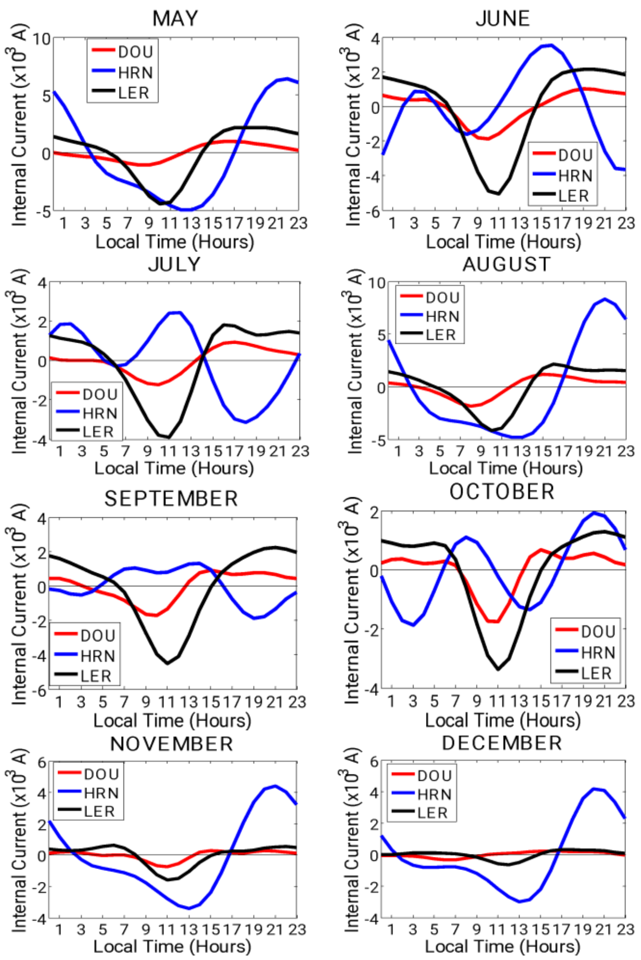
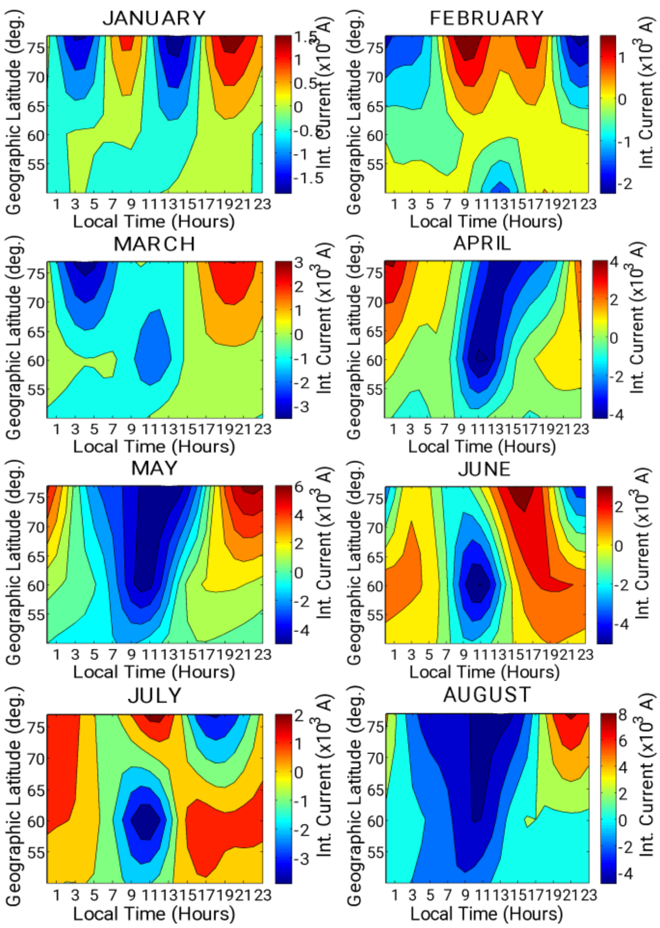


Fig 4. External Sq current across Europe (DOU, HRN and LER)



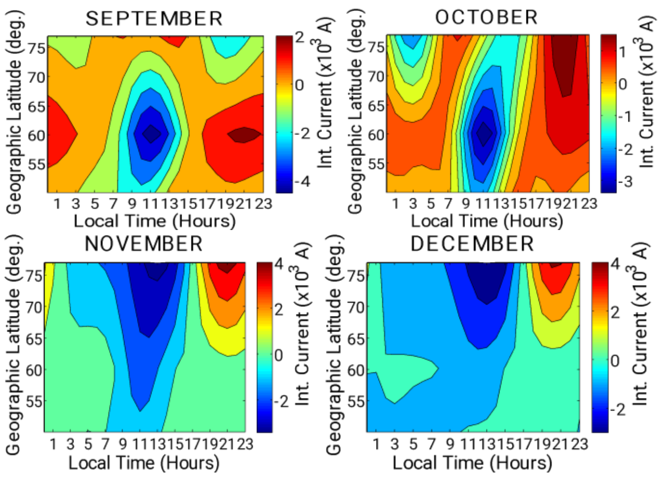


Fig 5. Contour map of internal current for mid and high latitudes of Europe

For the internal currents, maximum current was observed in September equinox at HER and DOU with a value of 1×10^3A and 1.8×10^3A respectively and in June solstice at HRN with a value of 4.45×10^3A

The external currents are expected to be maximum during the equinoctial seasons while a minimum is expected in local winter. For low latitude stations in the northern and southern hemispheres, maximum external currents are expected during the equinoxes or during local summer and minimum expected during local winter. This is so because during the equinoctial seasons, the sun is over the equator and maximum ionization occurs around the equatorial ionosphere. During the Solstice seasons, the sun rests above the northern and southern hemispheres.

Conclusion

Studying the ionospheric Sq current system at mid and high latitudes of Europe has been made possible by applying the solar quiet day ionosphere current.

From this data, we can draw the following conclusions:

1. The currents are observed to fluctuate from sunrise till dark.
2. The amplitude and phase of the source currents were different from the induced currents.
3. The currents and fluctuations in the geomagnetic components were found to vary with the seasons. The reason behind this is that the sun's position relative to the earth changes throughout the year.
4. In terms of the source current, the mid-latitude region shows the equinoctial maximum while the high-latitude region shows the solstice maximum.

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