



Effect of solar flare on the equatorial electrojet in eastern Brazil region

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The effect of solar flare, sudden commencement of magnetic storm and of the disturbances ring current on the equatorial electrojet in the Eastern Brazil region, where the ground magnetic declination is as large as 20° W is studied based on geomagnetic data with one minute resolution from Bacabal during November–December 1990. It is shown that the mean diurnal vector of the horizontal field was aligned along 2° E of north at Huancayo and 30° W of north at Bacabal during the month of December 1990. Number of solar flares that occurred on 30 December 1990 indicated the direction of solar flare related ΔH vector to be aligned along 5° E of north at Huancayo and 28° W of north at Bacabal. This is expected as the solar flare effects are due to the enhanced conductivity in the ionosphere. The SC at 2230 UT on 26 November 1990 produced a positive impulse in ΔX and negative impulse in ΔY at Bacabal with ΔH vector aligned along 27° W of north. At Huancayo the ΔH vector associated with SC is aligned along 8° E of north, few degrees east to the alignment of the diurnal vector of H . The magnetic storm that followed the SC had a minimum Dst index of -150 nT. The corresponding storm time disturbance in ΔX at Huancayo as well as at Bacabal were about -250 nT but ΔY at Bacabal was about $+70$ nT and very small at Huancayo, that give the alignment of the H vector due to ring current about 16° W of north at Bacabal and almost along N–S at Huancayo. Thus alignment of the ΔH vector due to ring current at Bacabal is 14° E of the mean direction of ΔH vector during December 1990. This is consistent with the direction of ring current dependent on the dipole declination at the ring current altitude which is about 5° W of north over Bacabal and the deviation of declination due to the ring current during disturbed period given by the angle $(\psi-D)$.

Keywords. Solar flare; equatorial electrojet.

1. Introduction

Chapman (1919) first derived the ionospheric current system based on northward (X) and eastward (Y) components of magnetic field at 21 observatories around the world. The current system derived, consisted of two loops in the sunlit hemisphere, centred at 1100 hr local time and

40° N and 40° S latitudes. The northern loop was anticlockwise and the southern loop was clockwise, spherical. Harmonic analyses were performed of the data from large number of observatories established during the IGY period to derive the ionospheric current system. All these analyses used only the H field and assumed that the potential of the field depends on the geographic

latitude and local time (Matsushita and Maeda 1965).

Parkinson (1971) used both the X and Y fields at about 50 observatories. Some terms depending on longitude as well as local time were included. The current pattern was found to be influenced by the asymmetry of the main field and the contours lines of H field for low latitudes were not parallel to the equator and were very much inclined in the region between South America and West Africa.

Riggotti *et al.* (1999) described the analyses of the data from an array of 29 vector magnetometers which operated in N–NE Brazil from November 1990 to March 1991. They derived a simple model of an equivalent current distribution for the Sq and equatorial electrojet (EEJ). Rastogi and Trivedi (2009) analyzed the data of X, Y and Z components of the magnetic field at stations in the Brazilian array. They showed that the variation of X showed a major maximum around 1200 LT. The daily variation of ΔY showed a strong minimum around noon at all stations. The direction of the deviation in the total horizontal field (ΔH) with respect to the geographic meridian (θ) was calculated using the relation

$$\theta = \arctan(\Delta Y/\Delta X)$$

and measured east of geographic north. The ΔH vector deduced from ΔY and ΔX was aligned along a direction about 25° W of north. Thus the equatorial electrojet currents are inclined to the geographic east by 25° towards north at the centre of the EEJ belt in this region. The centre of EEJ was found to be near 1.0° S dip latitude. These anomalies were suggested to be due to the abnormal distribution of the main magnetic field in the region. Rastogi *et al.* (2013) compared the characteristics of EEJ at Itinga in Brazil where D was 19.3° W and at Huancayo in Peru, where D was 1.0° E. The mean value of the diurnal H field vector was inclined about 20° W of north at Itinga and about 1° E of north at Huancayo. However, the hourly values for Itinga varied from about 6° W of north in the morning to 35° W of north in the afternoon. Day to day variations of H field at Huancayo and Itinga were highly correlated but there was no correlation (<0.2) in the daytime values of ΔY field at the two stations. Thus, the anomaly of electrojet current direction was characteristic of the east Brazil region.

Olson (1970) suggested that the magnetopause, neutral sheet and ring current make a measurable

contribution to the Earth's surface magnetic field besides the average Sq field. Sarabhai and Nair (1971) suggested that the ΔH , the daily variation of the horizontal component H at a low latitude station is caused by mainly the dynamo current at the ionospheric E region but are affected by the surface current at the magnetopause, the tail current, eccentric and partial ring current in the magnetosphere.

The enhancement of the horizontal component (H) of the geomagnetic field due to an X-ray flare event is called a Solar Flare effect (SFE). The maximum enhancement in H value over the pre-flare level indicates the magnitude, SFE (H) of an SFE event. The solar flare (magnetic crochet) related current was regarded as an augmentation of the Sq current system (Chapman 1961) in the past. Oshio *et al.* (1967) studied the solar flare effect on the geomagnetic field on a global basis and suggested that the seat of the ionospheric current is little lower than that of the Sq current system. McNish (1937) showed that the solar flare induced impulses in H field at low latitudes are aligned with the normal ΔH at the time of flare. Forbush and Casaverde (1961) showed that the enhancement of SFE in H over the dip equator in Peru varied in a manner similar to the Sq (H) variation in equatorial latitudes. Rastogi (2001a, b) studied the SFE in ΔH , ΔY and ΔZ at Trivandrum, close to the magnetic equator and Annamalainagar, a station at the edge of the equatorial electrojet in the Indian region for the period 1957–1982. It was shown that the SFE in ΔH at Trivandrum was positive during daytime with a broad maximum just before noon but the SFE in ΔY was positive in the forenoon and negative in the afternoon consistent with the effects expected of a normal Sq current. The mean hourly values of the SFE in ΔY were 2 nT or smaller. For Annamalainagar, the amplitude of SFE in ΔH was positive during daytime with peak around 0930 hr. SFE in ΔY was positive in the morning hours (06–08 hr) and negative during day time with minimum around noon similar to the variation of ΔY . There was no linear dependence of the amplitude of SFE in ΔY on the amplitude of SFE in ΔH at Annamalainagar. Rastogi (2003) studied SFE in the geomagnetic components ΔH , ΔY and ΔZ at Huancayo for the period 1957–1977 and showed the daily variations in conformity with the daily variations of the ΔH , ΔY and ΔZ . Further the SFE ΔY was shown to increase linearly with the increase of SFE ΔH at Huancayo. It must be pointed that the amplitude of the SFE in ΔY at Huancayo is

Table 1. *Coordinates, geomagnetic parameters at Huancayo and Bacabal for December 1990.*

Station name	Huancayo	Bacabal
Station code	HUA	BAC
Geog. latitude (deg)	12.0 S	4.2 S
Geog. longitude (deg)	75.3 W	44.8 W
Northward field, X (nT)	26,620	25,329
Eastward field, Y (nT)	452	-9234
Vertical field, Z (nT)	748	956
Horizontal field, H (nT)	26,624	27,007
Dip latitude (deg)	0.8	-0.8
Declination (ionosphere) D (deg)	1.0 E	20.0 W

much larger at Huancayo as compared to that at Trivandrum with mean hourly values of up to 12 nT.

It was felt important to check the direction of ionospheric current in the region of Eastern Brazil using the solar flare effects in ΔX and ΔY fields. Fortunately, there were a number of solar flares on 30 December 1990 and most of these occurred during daytime in Latin American region. In this paper, we have studied the SFE in ΔX and ΔY at Bacabal and Huancayo. The coordinates of the two stations are given in table 1. It is to be noted that the dip latitude at Huancayo was $+0.8^\circ$ and at Bacabal -0.8° , but the declination at Huancayo was 1.0°E while at Bacabal it was 20°W . Thus, the horizontal magnetic field H was deviated to only 1°E of north at Huancayo but 20°W of north at Bacabal.

2. Results

Plots of the hourly mean H vectors averaged over December 1990 for Huancayo and Bacabal are shown in figure 1 from the ΔX and ΔY values. Dotted lines show the direction in the figure. The daytime vectors at Huancayo are almost aligned along a straight line pointing to a direction of 2°E of north. For Bacabal daytime values lie along an elongated ellipse with individual values ranging from 20°W of north to more than 35°W of north and the major axis pointing to 30°W of north. The alignment of the ΔH vector is almost along the declination at Huancayo but about 10°W of the declination at Bacabal. Solar charged particle precipitation and meridional currents have been suggested for the anomalies seen in east Brazilian sector (Rastogi and Trivedi 2009). Further there are changes in the center

of electrojet with local time that can lead to changes in the direction of current (Rastogi *et al.* 2010).

Figure 2 shows the intensity of solar x-ray radiations in the two wave-length bands of 5–30 nm (shown by red line) and 10–80 nm (blue line) measured from GOES-6 satellite on 30 December, 1990 indicating a large number of solar flares that occurred on that day. It may be noted that the solar flare at 1027 UT corresponded to 1327 LT for Huancayo and 1527 LT for Bacabal. Similarly, the local times of the largest flare at 1515 UT were 1015 hr at Huancayo and 1215 hr at Bacabal.

Figure 3 shows the ΔH and ΔY variations at Huancayo on 30 December, 1990. It may be noted that ΔH at Huancayo will be almost equal to ΔX as the declination value is close to zero. Figure 4 shows the ΔX and ΔY magnetograms at Bacabal on 30 December, 1990. The amplitudes of ΔX and ΔY values in response to individual solar flares at Huancayo and Bacabal on 30 December 1996 are given in table 2. It can be seen that the SFE in ΔY at Huancayo were small in the range of 3–8 nT compared to the SFE in ΔX with values in the range of 30–78 nT. The SFE in ΔH are aligned in the range of 5° – 6°E of north with the mean direction of SFE vector about 5.4°E . At Bacabal the SFE in ΔY were in the range of -3 to -24 nT and the corresponding SFE in ΔX were in the range of 7–39 nT. The direction of the SFE in H varied from 23 to 32°W of north with the mean direction 28.7°W of north. Considering the accuracy of the measurements of the geomagnetic field to be 1 nT, the error in the computation of the direction of the H vector associated with the solar flare effects are about 1° at Huancayo and 2° to 10° for Bacabal. It may be noted that the mean direction of the SFE in H of 28.7°W of north is very close to the

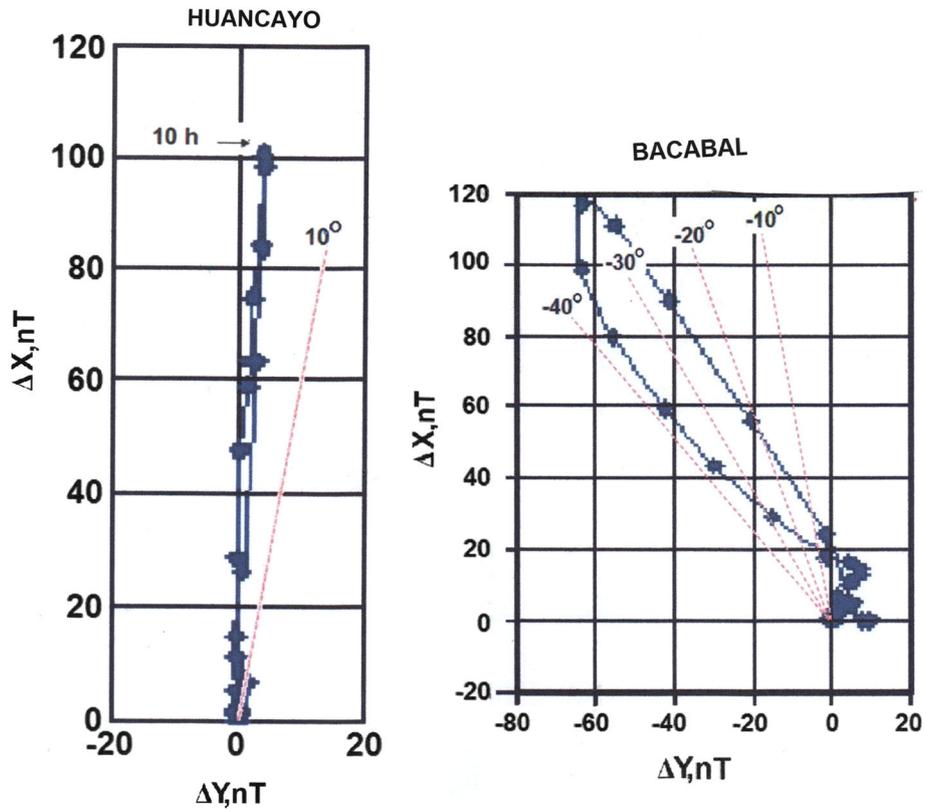


Figure 1. The monthly mean diurnal variation loops of ΔX and ΔY at Huancayo and Bacabal during December 1990.

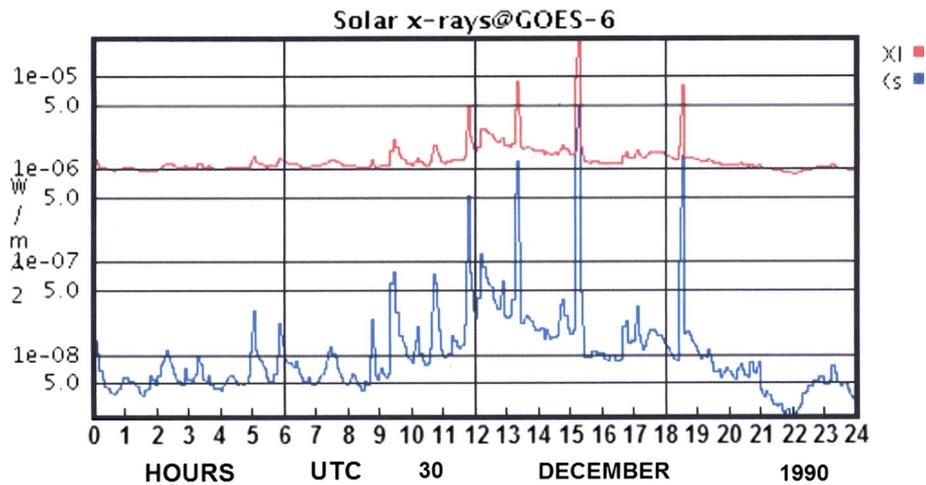


Figure 2. Solar X-ray flare plots on 30 December 1990 from GOES-6 Satellite.

direction of diurnal H vector at Bacabal ($30^\circ W$ of north).

3. Discussion

Based on a number of solar flares on 30 December 1990, the direction of solar flare ΔH vector was observed to be aligned along $5^\circ E$ of north at Huancayo and $28^\circ W$ of north at Bacabal. These are

close to the respective alignment of the monthly mean diurnal vectors of ΔH , along $2^\circ E$ of north at Huancayo and $30^\circ W$ of north at Bacabal during the month of December 1990. This is expected as the solar flare effects are due to the sudden enhancements of the conductivity resulting from the enhanced ionization in the D and lower E regions of the ionosphere. We have also computed the ΔH vectors at Bacabal and Huancayo associated with the SC at 2230 UT on 26, 1990. It was

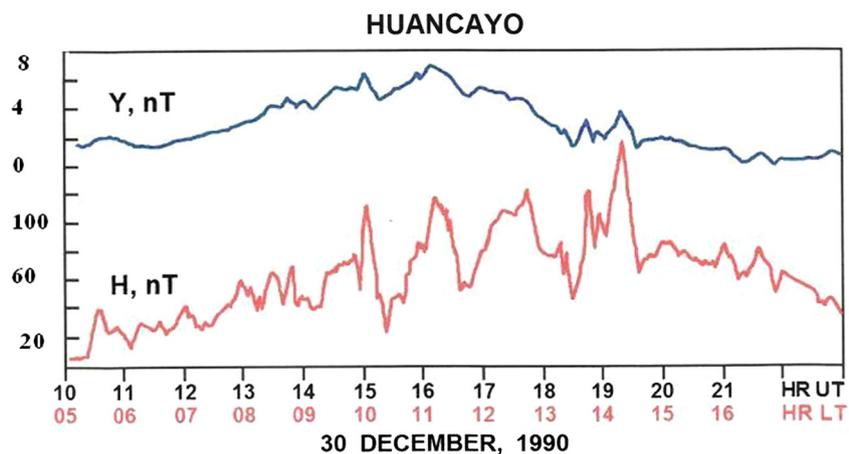


Figure 3. The daily plots of ΔH and ΔY at Huancayo, Peru on 30 December, 1990.

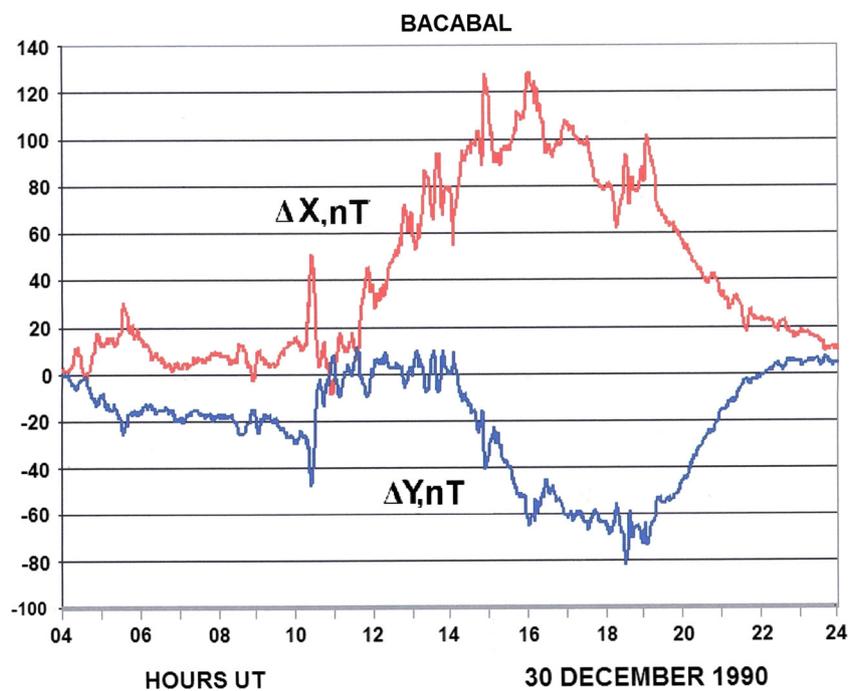


Figure 4. The daily plots of ΔX and ΔY at Bacabal, Brazil on 30 December, 1990.

Table 2. Amplitudes of crochet on 30 December 1990.

Time UT	Bacabal			Huancayo		
	ΔX (nT)	ΔY (nT)	$\theta^\circ E$	ΔX (nT)	ΔY (nT)	$\theta^\circ E$
0531	12	-7	-30.1	-	-	-
0831	7	-3	-23.3	-	-	-
1017	39	-22	-29.2	43	4	5.3
1138	34	-18	-27.9	43	4	5.3
1313	28	-14	-26.5	30	3	5.7
1515	39	-24	-31.4	55	5	5.1
1827	19	-12	-32.2	78	8	5.8
Mean			-28.7			5.4

aligned along 29°W of north at Bacabal, which is close to the alignment of the monthly mean diurnal vectors of ΔH at Bacabal. At Huancayo, the ΔY associated with the SC is small and the ΔH vector was aligned about 8°E of N. Considering the error involved of about 2° in computing, ΔH vector associated with SC is few degrees E to the alignment of the diurnal vector of H at Huancayo. The disturbance field of the SC is primarily due to two components. The DL component, an abrupt increase of the magnetopause current associated with the sudden compression of the magnetosphere dominates at low latitudes. DP component is dominant in the polar region and extends to lower latitudes due to a polar electric field transmitted along the magnetic lines of force from magnetosphere (Araki 1977). This field is significantly enhanced at the dayside dip equator. High latitude dusk to dawn electric field penetrates to low latitudes. The ionospheric currents due to this electric field will add to the normal ionospheric current. In addition to the magnetopause currents, there are secondary currents like the field-aligned currents, ionospheric current and tail current. The polarity of the IMF-Bz also plays an important role in the response to the solar wind dynamic pressure. Russell *et al.* (1994) studied the response of low-latitude H component during the passage of interplanetary shocks both during the northward and southward IMF-Bz conditions. They reported the largest SC amplitudes around noon during northward IMF and near midnight during the southward IMF. For the northward IMF magnetopause currents govern principally the amplitude of SC during dayside. Tail currents, which act in the opposite sense to magnetopause currents are also enhanced and have greater effect in the night than in daytime. In case of southward IMF, daytime response to solar wind pressure increases is over 25% smaller probably because of region 1 current system associated with dayside reconnection, however at night the mid and low-latitude response is much greater and attributed to the triggering of substorms in magnetotail. However, Clauer *et al.* (2001) reported an event with largest SC amplitude in night-time during a northward turning of IMF. Araki *et al.* (2006) examined a number of large amplitude SC events observed at Kakioka during the period 1924–1994. Large amplitudes SCs (H component larger than 40 nT) occur more frequently during the night time than the daytime. Three large amplitude SCs (more than 85 nT) showed largest amplitude near midnight in low latitudes except the dayside

equator. Further the case studies for two moderate amplitude SCs events at same UT showed that the nighttime SC amplitude are slightly (considerably) larger than daytime amplitudes when IMF points northward (southward). Diurnal variation of the SC amplitudes was explained by a combination of field-aligned and resultant ionospheric currents produced during the main impulse of SCs.

The magnetic storm following the SC had a minimum Dst index of -150 nT and the corresponding storm time disturbance in ΔX at Huancayo and Bacabal were about 250 nT. ΔY at Bacabal was about +70 nT and as expected very small at Huancayo. The alignment of the H vector associated with the ring current is about 16°W of north at Bacabal and almost along N–S for Huancayo. The alignment of the H vector due to ring current at Bacabal is 14° east of the mean direction of ΔH vector during December 1990.

Chandra and Rastogi (1997) studied the deviations in H , Y and Z at Kodaikanal in India for a large number of geomagnetic storms during 1970–1991. The ratio of $\Delta Y/\Delta H$ related to SC varied between -0.22 and -0.26 . Fukushima (1966) reported that most of the SC at Kakioka in Japan showed eastward declination changes and attributed this due to the declination (6°W) and the geomagnetic meridian (6°E of geographic meridian) at Kakioka. The storm time variations of the magnetic field at an equatorial electrojet station is due to the combined effect of the ring current and of the ionospheric currents associated with the electric field transmitted from high latitudes. Thus the alignment of the H vector due to the ring current could be different than that of the diurnal vector in H .

Fukushima (1966) had suggested that the impact of solar plasma on magnetosphere cause the magnetic field vectors of SC to align itself along the dipole meridian at the place. Rastogi *et al.* (2001) argued that the direction of the eastward component of the magnetic field due to ring current over a particular station should be given by the angle perpendicular to the dipole declination (ψ). Dipole declinations are the geomagnetic field vector at magnetospheric region measured with respect to the geographic meridian. Undisturbed direction of ΔH at ground is given by the declination D with respect to the geographic north. Thus the deviation of declination due to the equatorial ring current would be given by the angle $\psi-D$. Rastogi *et al.* (2001) also showed that the changes in ΔY , ΔH

during geomagnetic disturbances would be related by the relation

$$\Delta Y/\Delta H = \sin(\psi-D).$$

This was confirmed by examining the deviations in Y and H at few mid-latitude stations. The declination values were positively or negatively correlated with Dst index depending upon the sign of the angle $(\psi-D)$. Later James *et al.* (2004) examined the deviations in H and Y fields for the IGY period with Dst index at low latitude stations around the world and showed a good correspondence between $\Delta Y/\Delta H$ and $\sin(\psi-D)$ for all the stations in the equatorial belt. For the IGY period ground declination was 5°E at Huancayo and 19.2°W at Tatuoca (geographic latitude of 48.5°W). The dipole declinations at ring current altitude were 0.7°E for Huancayo and 4.2°W for Tatuoca. Looking at the contour plots of the angle ψ shown by James *et al.* (2004) its value at Bacabal would be about 5°W . Considering the ground declination of 20°W , the value of $\sin(\psi-D)$ comes out to be 0.26. Thus the ratio of $\Delta Y/\Delta H$ at Bacabal with a value of 0.28 for the event is very close to that obtained from the relation above.

Earlier studies in the East Brazilian region have shown that the direction of the ΔH vector changes with local time and season. The difference of few degrees in the alignment of the ΔH vector and the declination angle in the east Brazilian region was suggested to be due to the northward meridional current (Rastogi *et al.* 2010). As the polarity of IMF and the local time of SC play important role there is need for a detailed study in this region based on more case studies of the magnetic storm events.

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