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On the influence of the plasma generated by comet Shoemaker-Levy 9 on Jupiter's magnetic field(*)

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Summary. — The impact of comet Shoemaker-Levy 9 with Jupiter has created a variety of magnetospheric plasmas which were detected by their electromagnetic emissions. By means of the Dessler-Parker-Sckopke relation we estimate the perturbation of Jupiter's magnetic field. It appears that the produced plasma may explain the observed decrease of UV lines in Io's torus.

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1. – Introduction

The recent collision of comet Shoemaker-Levy 9 (SL-9) with the giant planet Jupiter during July 16-22, 1994, was a spectacular event which has produced an impressive and challenging data set [1]. These data contain very rich information on the comet, on Jupiter's atmosphere and on the impact itself. Therefore a great deal of work is needed to understand, starting from the observations, the physical processes at work. In this paper we analyze the influence of the plasma generated by the cosmic collision on Jupiter's magnetic field and magnetosphere, by using the Dessler-Parker-Sckopke relation and the data available through the new facility of World Wide Web (WWW) browsers of distributed databases developed on the Internet computer network.

2. – The Dessler-Parker-Sckopke relation

The impact of comet SL-9 with Jupiter has generated a substantial injection of plasma in Jupiter's magnetosphere. This plasma originates both from ion sputtering and pick

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up when the comet passes through Jupiter's radiation belts and from the ejecta at the impact sites. However, the detailed distribution of the plasma and energy released by SL-9 is far from being known. On the other hand, an order of magnitude estimate of the magnetic-field perturbation $\delta\mathbf{B}$ can be obtained from the virial theorem for a stationary magnetized system in a gravitational field [2]: dropping the energy terms of the planet alone (which satisfies the virial theorem) and overlooking the electric-field energy term (which is negligible in a planetary magnetosphere), the following generalized Dessler-Parker-Sckopke relation can be obtained [3, 4]

$$\frac{\delta B_z}{B^{\mathrm{J}}_{\mathrm{eq}}} = -\frac{2U^{\mathrm{m}}_{\mathrm{k}} + U^{\mathrm{i}}_{\mathrm{g}} + U^{\mathrm{m}}_{\mathrm{m}}}{3U_{\mathrm{D}}}, \tag{1}$$

where δB_z is the equatorial perturbation of the magnetic field (due to the cometary and/or magnetospheric plasma), the z-axis points to the North of Jupiter, $B^{\mathrm{J}}_{\mathrm{eq}}$ is Jupiter's dipole magnetic field at the planet's equator, $B^{\mathrm{J}}_{\mathrm{eq}} = \mu_{\mathrm{J}}/R^3_{\mathrm{J}} \simeq 4.2$ Gauss, with μ_{J} Jupiter's magnetic moment and $R_{\mathrm{J}} = 7.14 \times 10^9$ cm Jupiter's radius, $U^{\mathrm{m}}_{\mathrm{k}}$ is the kinetic energy of the magnetospheric plasma, $U^{\mathrm{i}}_{\mathrm{g}}$ is the gravitational interaction energy between Jupiter and the plasma, $U^{\mathrm{m}}_{\mathrm{m}}$ is the magnetic energy due to magnetospheric currents, and $U_{\mathrm{D}} = -\frac{1}{3}\mu_{\mathrm{J}} B^{\mathrm{J}}_{\mathrm{eq}}$ is the magnetic energy of Jupiter's dipole outside the planet surface ($B^{\mathrm{J}}_{\mathrm{eq}}$ is pointing southward and is therefore negative). Thus, eq. (1) gives the relative perturbation of the magnetic field at Jupiter as the ratio of energy terms of the magnetospheric plasma over Jupiter dipole magnetic energy.

3. – Preliminary estimates of δB_z

3˙1. *Magnetospheric plasma perturbation.* – We can obtain from eq. (1) preliminary estimates of the magnetic perturbations δB^{m}_z, due to the Jovian magnetospheric plasma, and $\delta B^{\mathrm{SL-9}}_z$, due to the cometary collision. The kinetic energy of the magnetospheric plasma is

$$U^{\mathrm{m}}_{\mathrm{k}} = \frac{1}{2}\int \rho v^2_{\mathrm{th}} \mathrm{d}V\,, \tag{2}$$

where ρ is the mass density and $v_{\mathrm{th}} = \frac{1}{2}\sqrt{\frac{2KT}{m}}$ is the thermal velocity. On the basis of the Voyager data, two main plasma populations are present in the Jovian magnetosphere, the so-called hot and cold components. For the hot-plasma component the temperature is $T \sim 30$ keV for both ions and electrons [5]. Assuming that the hot plasma is confined in the magnetospheric equatorial plane in a disc of half-thickness of $3R_{\mathrm{J}}$ [6] and that the radial dependence of the density is that given in [7], we find that the hot-plasma energy is of the order of $U^{\mathrm{m}}_{\mathrm{k}}(\mathrm{hot}) \simeq 1.5 \times 10^{26}$ erg. For the cold component [8] the thermal velocity is to be substituted by the bulk velocity, which has as an upper bound the corotation velocity $V_{\mathrm{corot}} = \Omega_{\mathrm{J}} r$, with $\Omega_{\mathrm{J}} = 1.76 \times 10^{-4}$ rad/s Jupiter's angular speed, while the equatorial disc half-thickness is of the order of $1R_{\mathrm{J}}$. Thus, the cold-plasma energy is $U^{\mathrm{m}}_{\mathrm{k}}(\mathrm{cold}) \simeq 6.62 \times 10^{25}$ erg. The magnetic energy of the magnetosphere is

$$U^{\mathrm{m}}_{\mathrm{m}} = \int \frac{B^2_{\mathrm{m}}}{8\pi}\,\mathrm{d}V\,, \tag{3}$$

where $B_{\rm m}$ is the magnetic field due to magnetospheric currents and is of the order of 5γ ($1\gamma = 10^{-5}$ Gauss) throughout the magnetosphere [9, 10, 7]. Assuming that the magnetosphere is $170R_{\rm J}$ long, $140R_{\rm J}$ large and $100R_{\rm J}$ thick, we obtain $U_{\rm m}^{\rm m} \simeq 8.6 \times 10^{25}$ erg.

Since $U_{\rm g}^{\rm i}$ is negligible in Jupiter's magnetosphere, and considering that the dipole magnetic energy is $U_{\rm D} = -\frac{1}{3}\mu_{\rm J} B_{\rm eq}^{\rm J} = 2.14 \times 10^{30}$ erg, the perturbation of the magnetic field $\delta B_z^{\rm m}$ due to the magnetospheric plasma is

$$\text{(4)} \qquad \frac{\delta B_z^{\rm m}}{B_{\rm eq}^{\rm J}} = -\frac{2\big[U_{\rm k}^{\rm m}({\rm hot}) + U_{\rm k}^{\rm m}({\rm cold})\big] + U_{\rm m}^{\rm m}}{3U_{\rm D}} \simeq -\frac{5.2 \times 10^{26}{\rm erg}}{6.4 \times 10^{30}{\rm erg}} = -0.8 \times 10^{-4}\,.$$

Therefore the equatorial depression of Jupiter's magnetic field $\delta B_z^{\rm m}$ is of the order of 35γ: whereas this perturbation is small close to the planet, it is very important in the magnetosphere, for instance at 15 $R_{\rm J}$ from Jupiter, and corresponds to the well-known magnetodisc configuration of Jupiter's magnetosphere.

3·2. *Cometary plasma perturbation.* – Let us now consider the comet SL-9. We note that just before the impact the kinetic energy $U_{\rm k}^{\rm SL\text{-}9}$ is very close in absolute value to the (negative) gravitational energy $U_{\rm g}^{\rm SL\text{-}9}$, as most of the comet acceleration occurs in the vicinity of the planet. Therefore, the numerator at the r.h.s. of eq. (1) equals $U_{\rm k}^{\rm SL\text{-}9}$, in practice (it is known that the comet magnetic energy is negligible). On the (unlikely) assumption that all the collision kinetic energy of the comet is converted to thermal energy of the magnetospheric gases, we can give an upper limit for the magnetic-field perturbation. The impact velocity of SL-9 is 60 km/s [1]; assuming that about ten fragments have a diameter of 1 km [11] and a density twice that of water yields $U_{\rm k}^{\rm SL\text{-}9} \simeq 3.6 \times 10^{29}{\rm erg}$. Inserting the above value in eq. (1) we obtain an upper estimate of $\delta B_z^{\rm SL\text{-}9}$ as

$$\text{(5)} \qquad \frac{\delta B_z^{\rm SL\text{-}9}}{B_{\rm eq}^{\rm J}} \simeq -\frac{U_{\rm k}^{\rm SL\text{-}9}}{3U_{\rm D}} = -\frac{3.6 \times 10^{29}{\rm erg}}{6.4 \times 10^{30}{\rm erg}} = -5.6 \times 10^{-2}\,.$$

This perturbation is so conspicuous, that the magnetospheric configuration would change dramatically. In other words, the global effect of the cometary impact is potentially much larger than that due to Jupiter's huge magnetosphere. However, we must consider that that part of the comet which is swallowed by Jupiter does not contribute to the kinetic energy of the magnetospheric plasma $U_{\rm k}^{\rm m}$. Thus, one has to estimate how much and how energetic plasma was produced by the comet.

4. – Observations of plasma generated by comet Shoemaker-Levy 9

A worldwide observation campaign has allowed to collect, together with many exciting images, several evidences of SL-9–accelerated plasma in Jupiter's magnetosphere. The signature of these plasmas is given by their most energetic component which stimulates electromagnetic radiation. A great number of observations were distributed electronically: among these, we can list the following (the source reported in parentheses is the data location for a WWW browser on Internet):

a) The Hubble Space Telescope (HST) detected UV flashes in the northern hemisphere of Jupiter, indicating streaming of (very) high-energy particles along **B** in connection with impacts [1], fig. 1.

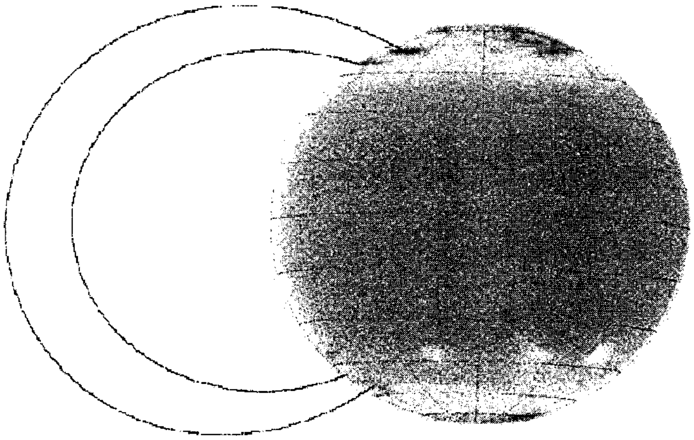

Fig. 1. – This far ultraviolet image of Jupiter, here shown in negative, was taken with NASA's Hubble Space Telescope and shows auroral bright spots that appeared at northern mid-latitudes following the impact of the K fragment of comet SL-9. The impact regions, which appear as white areas on the background of Jupiter's UV radiation, are in the southern hemisphere at about 40°–45°, with the K impact region on the left limb. The magnetic-field lines connecting the impact region and the bright spots are sketched. The image was taken on July 19, 1994, 45 minutes after the K fragment slammed into the giant planet, with the Wide Field Planetary Camera-2 at 130–210 nm. At these wavelengths the polar regions normally appear dark and the northern and southern auroras are clearly visible (credit: John T. Clarke (U. of Michigan) and NASA; image in http://newproducts.jpl.nasa.gov/sl9/gif/hst23.gif).

b) The ROSAT High Resolution Imager detected X-rays emission from Jupiter northern hemisphere during fragment K impact, probably due to streaming electrons and correlated with the HST UV flashes (http://newproducts.jpl.nasa.gov/sl9/rosat2.html).

c) The International Ultraviolet Explorer (IUE) detected hydrogen plasma production in the ejecta of fragments K and P2, indicated by Ly-α emission in the plumes (http://www.vilspa.esa.es:8000/iue_update_2107.html).

d) The ESO New Technology Telescope Infrared Spectrometer (NTT-IRSPEC) at La Silla, Chile, observed infrared bright features in the northern hemisphere, exactly opposite to large impact sites, at a latitude of $+44°$. These are attributed to H_3^+ emission [12], which is typical of Jupiter's auroral phenomena (ESO SL9 News Bulletin in http://http.hq.eso.org/educnpubrelns/esorepjul26.txt).

e) The NASA Extreme Ultra-Violet Explorer (EUVE) detected He^+ ions produced at high altitudes in Jupiter's atmosphere during impacts, indicating heating to very high temperatures (http://cea-ftp.cea.berkeley.edu/EGO/JUP940722.html).

f) During a two-minute period on July 14, when fragment G of comet SL-9 entered the magnetosphere, HST detected strong emissions from ionized magnesium (Mg II), an important component of both comet dust and asteroids, showing *in situ* plasma generation (http://newproducts.jpl.nasa.gov/sl9/hst15.html).

In addition to the above observations reported on Internet, a significant increase in the synchrotron emission from Jupiter's radiation belts, due to electrons in the 10 MeV energy range, was also detected. This shows that the cometary collision created very energetic particles, too.

5. – Conclusions

Although the above observations clearly indicate that the comet SL-9 has caused a number of magnetospheric phenomena, at this time it is not possible to estimate how much energy went into the plasma produced by the comet. In particular, the global amount of SL-9–generated plasma may be much larger than that which triggers detectable electromagnetic emission. Therefore we can only make speculative guesses. For instance, if 10^{-4} of the available energy went into the magnetospheric plasma, *i.e.* $U_{\mathrm{k}}^{\mathrm{m}} = 3.6 \times 10^{25}$ erg, the perturbation of the magnetic field would be

$$\frac{\delta B_z^{\mathrm{SL-9}}}{B_{\mathrm{eq}}^{\mathrm{J}}} = -\frac{3.6 \times 10^{25}\mathrm{erg}}{6.4 \times 10^{30}\mathrm{erg}} = -0.6 \times 10^{-5}\,, \tag{6}$$

that is, an order of magnitude smaller than the perturbation due to the magnetosphere, eq. (4). This would modify only slightly the magnetospheric configuration, and agrees with the fact that no significant changes were seen in Jupiter's radio emission by the URAP experiment onboard the Ulysses spacecraft (http://server64h.jpl.nasa.gov-/ulysses5/4Comet.html). However, the above perturbation stimulates the search for features that may be hidden by the normal variability of Jupiter's radio emission. Furthermore, the simultaneous *decrease* of all the Io torus UV spectral lines observed by EUVE in coincidence with the impacts (http://cea-ftp.cea.berkeley.edu/EGO/JUP940722.html) most likely is not due to cometary material, but rather to a global perturbation of the torus structure. In particular, this may be a decrease in the torus plasma density associated with an increase in the interchange-instability–driven plasma transport [13] which can be triggered by a magnetic-field perturbation due to the impact of the cometary fragments.

Finally, we point out the relevance of computer networks, which allowed us to obtain data and images, in the diffusion of scientific information [14]. "The Shoemaker-Levy 9/Jupiter collision was the first time that observations of a major astronomical event were coordinated and results distributed immediately mainly using the Internet. The new tools (principally WWW browsers), along with faster and more extensive networks (stretching even to the South Pole), meant that observations often appeared on the World Wide Web within hours of being obtained [...]. Despite the huge increase in load the Internet survived the experience and allowed a widely distributed group, the majority of which were probably not professional astronomers, to become involved in a unique and highly successful global observation campaign." (Adapted from ESO SL9 News bulletin in http://http.hq.eso.org/educnpubrelns/esorepjul26.txt).

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