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Impacts of comets onto the Sun and coronal mass ejections.

I. Nemtchinov (1), I. Kosarev (1), A. Kovalev (1), T. Losseva (1), V. Shuvalov (1), R. Treumann (2)

(1) Institute for Dynamics of Geospheres RAS, Moscow, Russia,

(ivvan@idg.chph.ras.ru), (2) Max-Planck Institute for Extraterrestrial Physics, Garching, Germany

As much as 300 sun-grazing comets were observed between January 1996 and June 2001 by the sensitive Solar Heliospheric Observatory (SOHO) instrumentation capable of detecting faint objects. The average number of sun-grazers is 60 per year. A comet was discovered that did not reappear after the time of closest approach to the Sun. Much later, extremely broad diffuse brightening of the corona over one solar hemisphere was observed. This brightening was interpreted as having been caused by the cometary debris back-scattered into the ambient solar wind.

One June 11, 1998, two sun-grazing comets following similar but not identical orbits were viewed. Shortly after they disappeared behind the occulting disks of the coronographs, a coronal mass ejection (CME) with an enormous erupting prominence appeared on the limb of the Sun. Observations like these raise the question of whether these have been pure coincidences or whether, if only in some cases, there exists a causal link between cometary impacts on the Sun and the release of CMEs. Here we present the first results of an attempt to infer whether CMEs can in principle be caused by cometary impacts on the Sun.

The typical mass a CME lifted against the solar gravity is of the same order of magnitude the mass of a 1 km icy sphere. The energy released in the impact of such a comet may be sufficient to produce a “directly driven” CME, when the sudden release of thermal energy in the corona (“thermal blast”) creates a highly enhanced gas pressure that cannot be contained by the solar magnetic field. In this case the corona is literally blown open, intense shock waves are generated, propagating out to large distances from the Sun. Historic evidence shows that among sun-grazers there were several large comets. Our previous investigations have shown that large impactors may deeply penetrate into the solar photosphere (e.g. down to an altitude of about 1500 km for a comet 30 km in radius). Energy of these impactors is sufficient for direct ignition of a CME. But impacts of large bodies are rather infrequent, while there are 270 to about 1500 CMEs per year. It is obvious that the main part of the relatively faint sun-grazers is rather small and their mass and energies are much less than those of a typical CME.

Currently the best accepted model of generation of CMEs refers to “stored and released” coronal magnetic energy. This model proposes that CMEs are triggered by micro-instabilities causing anomalous resistivity, current dissipation, and reconnection. The energy fuelling the CME is stored in the corona. The energy of the impactors which may initiate the evolution of micro-instabilities, reconnection of magnetic field lines and ultimately trigger a CME may be substantially less than the final energy of CME. So we should investigate the peculiar properties of impacts of small comets, which previously have not been studied thoroughly.

Simple estimates show that near the Sun the mass of an icy comet evaporated during its approach to the Sun under the action of solar radiation is equivalent to the mass of an icy layer about 100 m thick. Therefore, small sun-grazers may be fully evaporated. These estimates should, however, be corrected as the surface of the comet reaches temperatures much higher than the temperature of volatile evaporation. This claim is supported by the observation of the light curves which show that the normalized brightness depends only on the heliocentric distance of the comet. That can be understood if we assume that the maximum temperature is given by the equilibrium blackbody temperature T_B. At temperatures of 1600 to 2700 K the refractory material becomes intensely evaporated, while volatiles may evaporate at smaller heliocentric distances.

The determination of the ablation is made more difficult by the complicated radiation transfer processes in the vapour layer. Detailed spectral absorption coefficients in a wide range of temperatures, densities and spectral intervals (in the IR, visible and UV wavelength ranges) were calculated for typical volatile-rich cometary substances and for chondritic components, which may represent a comet after the evaporation of ices. The analysis of these coefficients shows that the evaporating surface is at least partially screened by the vapour layer.

Because of the multitude of molecule absorption bands and lines involved, one needs to introduce a very large number of spectral intervals in order to infer about the real radiation spectrum. The spectral methods for solving the radiation hydrodynamic problem taking into account the detailed spectrum and angular dependence of the radiation have been developed and used to determine the temperature profile in the vapour layer and the mass ablation rate taking into account both screening of the surface and re-radiation.

It is usually assumed that disruption of comets in the atmosphere occurs due to aerodynamic loading during the flight through the dense layers of the atmosphere. Under the action of these aerodynamic forces the comet is deformed in the atmosphere of a planet in a liquid-like manner. In the case of impacts onto the hot Sun in addition to the tidal forces and thermal stresses the ejection of vapour streams from the intensely evaporated surface play an important role. These forces act onto the comet's surface not only during a rather short (several seconds) time interval when the cosmic body passes across the dense layers of the atmosphere. They become rather strong at large heliocentric distances - of the order of one or even several solar radii. The pressure at the surface of the comet is larger than the typical strength of comet. Within the long time of flight (of the order of an hour and more) the cometary body will thus disintegrate. A swarm of fragment surrounded by vapour clouds will thus move to the Sun. Since these fragments have all different sizes some sorting will occur.

Estimates of the vapour density near the surface yield values of the order of 10^{-5} g/cm^3. During the expansion of the vapour cloud its density decrease and the peripheral layers of the cloud become transparent to the incident radiation. The expansion velocity at maximum temperatures in the range 2000-4000 K is about 1-3 km/s. During the process of vapour expansion and coma formation the density in the outer layers gradually becomes comparable to that of the solar atmosphere.

During the passage of a large comet to the Sun the maximum and average densities of the coma remain approximately at the same level. But from the moment on when the comet becomes fully evaporated the maximum and average densities of the vapor cloud do rapidly decrease. The bigger the body is and the larger time of its evaporation, the larger is the depth of penetration. At the contrary, the earlier the time of full evaporation is, the larger is the altitude of energy release.

The processes of deforming of the vapor cloud and becoming turbulent have been analyzed with the help of numerical simulations similar to those performed for the Jupiter impacts.

The formation of a wake behind the descending comet or vapor cloud facilitates the rise of the plume ascending from the region of energy release. The velocities of ejection are of the same order of magnitude as the escape velocity. The outward propagating shock waves will interact with the solar magnetic field. Intense radio emission similar to that which has been detected in the natural CMEs will be generated in these processes.

Phenomena analogous to CMEs should occur also at other stars whose magnetic and gravitational fields are sun-like. During the formation of extrasolar systems the number of impacts may be much more frequent than on the Sun in the modern epoch. Spectroscopic observations has shown that at least at young stars the infall of evaporating bodies may happen rather frequently, but direct impacts and their associated impact-generated CMEs have not yet been observed.

Observation of optical flashes (fireworks) released from collisions between planetesimals in the phase of planet formation could be used to detect extrasolar systems. The efficiency of light emission during impacts onto a gaseous body is higher than in the case of collisions between solid bodies. This is what initiated our investigation of cometary impacts onto the Sun and planetesimals onto a star. In addition to the visible range the radiation in the EUV and x-ray bands has also been studied.

Radio technique methods of detection of radio emissions have high sensitivity. The detection of radio bursts from impacts, particular from the shock waves produced, may be even more efficient than the detection of optical flashes in the visible and emissions in the XUV.