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Explosion of sungrazing comets in the solar atmosphere and solar flares

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Abstract. Explosive evolution of nuclei of sungrazing comets near the solar surface, which occurs at conditions of intense interaction between the solar atmosphere and falling high-velocity comet nuclei as well as the relation of the phenomenon to the character of solar activity are analytically considered. It is found that, due to aerodynamic fragmentation of the falling body in the solar chromosphere and transversal expansion of the fragmented mass under the action of pressure gradient on the frontal surface, thermalization of the kinetic energy of the body occurs by sharp stopping of the disklike hypervelocity fragmented mass near the solar surface within a relatively very thin subphotospheric layer and has, therefore, an essentially impulsive and strongly explosive character. The specific energy release in the explosion region, erg/g, considerably exceeds the evaporation/sublimation heat of the body so that the process is accompanied by production of a high-temperature plasma. The energetics of such an explosive process corresponds to that of very large solar flares for falling bodies having masses equal to the mass of the nucleus of Comet Halley. Spectral observations of sungrazing comets by SOHO-like telescopes in a wide spectral range, including X rays, with a high time resolution, of the order of 0.1–10 s, are important for revealing solar activity in the form of an impact-generated photospheric flare.

Keywords. comets: general; Sun: flares; explosions

1. Introduction

Coronagraphic observations by SOLWIND (Solar Wind), SMM (Solar Maximum Mission) and SOHO (Solar and Heliospheric Observatory) missions indicate the presence of a continuous comet flow passing close to the solar surface or colliding with the Sun (Weissman 1983; Marsden 1989; MacQueen & St. Cyr 1991; Bailey *et al.* 1992; COSPAR 1998). Passages of cometlike bodies, extrasolar comets, near young stars may be responsible for observed changes in stellar spectra, for the origin of the Beta Pictoris like phenomenon, due to evaporation of these bodies (see, e.g., Beust *et al.* 1996, Ibadov *et al.* 2007, and references therein).

At the same time disintegration process of nuclei of sungrazing comets being considered in the framework of traditional sublimation model, i.e., by the action of the solar photospheric thermal radiation, leads to an insignificant decrease in the comet nucleus radii, attaining not more than 20 metres (Weissman 1983; MacQueen & St. Cyr 1991).

We are developing an analytical approach to investigate the evolution of comet nuclei under the conditions of intense interaction between the solar atmosphere and falling nuclei resulting in their aerodynamic fragmentation as well as the relation of the phenomenon to the character of solar activity.

2. Disintegration of comets in the solar atmosphere

The law for velocity variation of fully fragmented comet nuclei with initial radii $R_0 \gtrsim 100$ m in the region close to the endpoint of the deceleration trajectory in the solar atmosphere with the mass density distribution like $\rho_a = \rho_0 \exp(-z/H)$ (Ivanov-Kholodnyi & Nikol'skii 1969) , i.e., at small distances from the solar surface, $z \ll \tilde{z} \ll z_*$, has the following form:

$$V = \tilde{V} \exp\left[-\frac{2b^2}{3C_x C^2}\left(r^2 - \tilde{r}^2\right)\right] = V_0 \exp\left(-\frac{2b^2}{3C_x C^2}\, r^2\right). \tag{2.1}$$

Here V_0 is the initial orbital velocity of the comet nucleus above the solar photosphere,

$$b = \nu \exp\left(-\frac{z_*}{H}\right); \quad \nu = \frac{3C_x \rho_0 H}{4\rho_n R_0 \sin\alpha}; \quad C = \left(\frac{3C_x R_0 \sin\alpha}{8H}\right)^{1/2}; \tag{2.2}$$

$$r = \left[\exp\left(\frac{z_* - z}{H}\right)\right] - 1; \quad \tilde{r} \approx \frac{4C^2}{b}. \tag{2.3}$$

Furthermore, C_x is the coefficient of the aerodynamic drag; $\tilde{r}$, $\tilde{z}$ and $\tilde{V}$ are the characteristic values of r, z and V, which correspond to the value of $R = 2R_0$, i.e., to the time instant when the nucleus is completely fragmented and its transverse radius is equal to the doubled value of the initial radius (Grigoryan *et al.* 1997; Grigoryan *et al.* 2000), R_0 and ρ_n are the initial radius and the density of the nucleus respectively; α is the angle between the entry velocity of the nucleus into the atmosphere and the horizon.

From (2.1) and (2.3) it follows that the basic deceleration of the nucleus, the decrease in its velocity from $V_1 = 0.9V_0$ to $V_2 = 0.1V_0$, occurs at $r_2^2(z_2) = 9r_1^2(z_1)$, i.e., in the trajectory segment lying, according to (2.3), in the height range

$$|\Delta z| = |z_2 - z_1| = H \ln\frac{1 + r_1}{1 + r_2} \approx H \ln\frac{r_1}{r_2} \approx 0.7H. \tag{2.4}$$

Using (2.1) we can also obtain an explicit expression for the characteristic value of $r = r_e$ at which the kinetic energy of the fragmented mass falls e times, namely $V = V_0/\sqrt{e}$ at

$$r_e = \frac{\sqrt{3C_x}C}{2b}. \tag{2.5}$$

According to (2.2), (2.3) and (2.5), the height corresponding to the value of $r = r_e$ is

$$z_e = z_* - h \ln(1 + r_e) = H \ln\left(\frac{2b\rho_0 V_0^2}{\sqrt{3C_x}C\sigma_*}\right). \tag{2.6}$$

Assuming $R_0 = 1\,\text{km} = 10^5$ cm, $\sigma_* = 10^4$ dyn/cm^2, $\rho_n = 0.5$ g/cm^3, $C_x = 1$, $\sin\alpha = 0.5$, $H = 1.5 \times 10^7$ cm, from (2.2), (2.3), (2.5) and (2.6) we find $\nu = 4.5 \times 10^{-5}$, $z_*/H = 8$, $b = 1.3 \times 10^{-8}$, $C = 3.5 \times 10^{-2}$, $\tilde{r} = 4 \times 10^5$, $r_e = 2 \times 10^6$, $R(r_e) = 30R_0$, $z_e = -12H = -1800$ km, $\Delta z = 0.7H = 100$ km. So, aerodynamic fragmentation of a comet nucleus in the solar chromosphere is accompanied by transverse expansion of the fragmented mass and explosion of this high-velocity mass in a relatively very thin subphotosphere sheet: the characteristic timescale of the explosion, thermalization of the kinetic energy of the mass, is of the order of 0.1–1 s.

The specific energy release in the explosion zone, $V^2/2 = 1.8 \times 10^{15}$ erg/g, significantly exceeds the evaporation/sublimation heat of the nucleus material, $E_s = 8 \times 10^{10}$ erg/g, so that the fall of comets onto the Sun will be accompanied by not only evaporation but also production of a plasma with an initial temperature higher than 10^6 K near the solar photosphere (Grigoryan *et al.* 2000).

The energetics of the process is of the order of 10^{32} erg for a falling mass of the order of 10^{17} g, which corresponds to the mass of the nucleus of Comet Halley 1986 III.

The astrophysical manifestation of the process may be, for instance, an excess of radiation in bright lines of metal atoms during the expansion of the generated high-temperature plasma having a timescale of the order of 10–100 s; a similar process was observed during the collision of Comet Shoemaker–Levy 9 with Jupiter on 16–22 July 1994 (Fortov *et al.* 1996).

3. Conclusion

The passage of comets near the solar surface is accompanied by aerodynamic fragmentation of their nuclei within the solar chromosphere and transverse expansion of the fragmented mass. The sharp stopping of this high-velocity fragmented mass is accompanied by production of a high-temperature plasma near the solar photosphere and by a solar photospheric flare.

The spectral monitoring of solar radiation and sungrazing comets in bright lines of metal atoms and ions involving not only the visual range but also soft X rays with a time resolution of 0.1–10 s is worthwhile.

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