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Stellar ejecta from falling comet-like bodies: young stars

Firuz S. Ibodov[1] **and Subhon Ibadov**[1,2]

[1]Lomonosov Moscow State University, Sternberg Astronomical Institute, Moscow, 119234 Russia
email: mshtf@sai.msu.ru

[2]Institute of Astrophysics, Tajik Academy of Sciences, Dushanbe, Tajikistan
email: ibadovsu@yandex.ru

Abstract. High-resolution spectral observations of young stars with dense protoplanetary discs like Beta Pictoris led to the discovery of variable emission lines of metal atoms, Na, Fe etc., that indicate the presence of fluxes of comet-like evaporating bodies falling onto the stars, FEBs. Assuming the presence of stellar atmospheres similar to the solar one, we show that passages of the FEBs through the stellar chromosphere and photosphere with velocities around 600 km/s will be accompanied by aerodynamic crushing of the nuclei, transverse expansion of the crushed matter, "explosion" of the flattened nuclei in a relatively very thin sub-photosphere layer due to sharp deceleration, and impulse production of a hot plasma. The impulsive rise of the layer's temperature and density lead to the generation of a strong "blast" shock wave and shock wave-induced ejection/eruption of hot plasma into space above the chromosphere. Observations of such impact-induced high-temperature phenomena are of interest for the physics/prognosis of stellar/solar flares as well as physics of comets.

Keywords. stars: individual (β Pic); stars: flare; comets: general; shock waves; Sun: coronal mass ejections (CMEs)

1. Introduction

Coronagraph observations by SOLWIND, SMM, SOHO and STEREO missions, together with ground-based observations and celestial-mechanics calculations of the orbital evolution of comets, indicate the presence of a continuous comet flux passing close to the solar surface or colliding with the Sun (Weissman 1983; MacQueen & St.Cyr 1991; Bailey *et al.* 1992; Info 1998; `http://sungrazer.nrl.navy.mil/`).

At the same time, high-resolution spectral observations of young stars with dense protoplanetary discs, like β Pictoris, led to the discovery of variable emission lines of metal atoms, Na, Fe, etc., that indicate the presence of fluxes of comet-like evaporating bodies falling onto the stars, FEBs (Lagrange *et al.* 1987; Beust *et al.* 1996; Grinin *et al.* 1996).

We are developing an analytical approach for investigating processes accompanying the passage of star/Sun impacting comet-like bodies through their atmospheres and the relation of these processes to active ones on the stars, assuming the stellar atmospheres are similar to the solar atmosphere.

2. Impulse aerodynamic deceleration of crushed comet nuclei in the solar/stellar atmosphere: explosive photospheric mass ejection

The height range of basic deceleration of the aerodynamically fully fragmented and transversally expanding nucleus where the decrease of velocity from $V_1 = 0.9V_0$ to $V_2 = 0.1V_0 = 60$ km/s occurs is $\Delta h_{\rm d} \approx 0.7H = 140$ km (Grigorian *et al.* 1997, 1998, 2000; Ibadov *et al.* 2009).

The characteristic time for thermalization of the kinetic energy of the fragmented mass in the decelerating layer, $\tau_{\rm th} = \Delta h_{\rm d}/V_{\rm e} = 0.7eH/V_0 \approx 0.5$ s, indicates the strongly impulse/explosive character of the energy release process that leads to generation of a hot plasma and strong shock wave.

The initial velocity of "blast" shock wave in the explosive layer is estimated as

$$V_{\rm sh} = \left[\frac{kT_0}{2\pi A m_{\rm p}} + \frac{3k(1+z)T_0}{A m_{\rm p}}\right]. \tag{2.1}$$

Here T_0 is the initial plasma temperature, $T_0 = A m_{\rm p} V_{\rm e}^2 / \left[12k\,(1 + z + 2x_1/3)\right]$, A is the mean atomic number for the falling comet nucleus material and matter of the solar photosphere, $m_{\rm p}$ is the proton mass, k is the Boltzmann constant, z is the mean multiplicity of charge of plasma ions, x_1 is the mean relative ionization potential (Ibadov 1986, 1990, 1996; Ibodov & Ibadov 2011).

The maximum height of the photospheric mass ejections due to cometary impacts may be estimated as

$$h_{\rm m} = \frac{V_{\rm sh}^2}{2g_0} = \frac{R_0^2 V_{\rm sh}^2}{2GM_0}, \tag{2.2}$$

where g_0 is the gravity acceleration on the solar/stellar surface, G is the gravitational constant, and M_0 is the mass of the Sun/star.

Accepting realistic values of $A = 20$, $z = 5$, $x_1 = 3$ and using (2.1), (2.2) with $M_0 = 2 \times 10^{33}$ g we get $T_0 = 7 \times 10^6$ K, $V_{\rm sh} = 1.7 \times 10^7$ cm/s, $h_{\rm m} = 5 \times 10^9$ cm.

It is known that there is a variety of solar prominences having maximum heights in the range 30–50 thousand kilometers (Mackay *et al.* 2010 and references therein). It means that comet impact-generated photospheric mass ejections can form a certain type of solar/stellar prominences, too.

Application of results of our consideration is possible for studying, analytically, the collision of comet SL 9 with Jupiter in July 1994: "plumes" have been detected up to maximum heights around 3500 km by the HST (e.g., Hammel *et al.* 1995).

The physics of a similar explosive event in the Earth's atmosphere, known as the 1908 Tunguska phenomenon, has analytically been developed during several last decades (Grigorian 1979; Ibadov *et al.* 2008, 2010; Grigorian *et al.* 2009, 2013).

3. Conclusions

The passage of comet nuclei through the solar/stellar chromosphere is accompanied by intense aerodynamic crushing, transverse expansion of crushed matter, sharp aerodynamic stopping in a relatively very thin sub-photosphere layer, impulse production of a hot plasma, strong "blast" shock wave, ejection/eruption of a hot "plume" consisting of photospheric and cometary material to the heights reaching the lower solar corona.

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