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INTERSTELLAR DUST AS GENERATOR OF X-RAY RADIATION

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Summary. The X-ray generation due to arising of hot dense plasma balls at high-velocity (≥ 70 km s^{-1}) collisions of dust grains in the interstellar medium is considered. Analitical expressions for efficiency of conversion of colliding dust particles kinetic energy into X-ray radiation are presented. The observed intensity distribution of the diffuse component of soft cosmic X-rays (0.1-1 keV) may be partly caused by collisions between the dusty components of high-velocity clouds and of the disk of our Galaxy.

Key words: interstellar dust grains - high-velocity collisions - X-ray generation

1. Introduction

Observations of the diffuse component of cosmic soft X-rays (0.1-1 keV) have indicated that most of these X-rays are emitted from the interstellar medium of the Galaxy by a hot plasma located within 100-200 pc around the Solar system (see e.g. Tanaka and Bleeker, 1977; Apparao, Hayakawa and Hearn, 1979; Kaplan and Pikelner, 1979; Syunyaev, 1986).

There are two approaches to the problem of hot interstellar plasma origin which are connected with the galactic supernova explosions at sufficiently high rate (Cox and Smith, 1974) and the strong stellar wind around early type stars (Castor, McCray and Weaver, 1975). The search for mechanisms responsible for the observed distribution of diffuse soft cosmic X-rays is continuating (Ibadov, 1981; Hirth, Mebold and Müller, 1985).

Interstellar dust is one of the abundant, universal components of the interstellar medium, especially in the directions of the galactic plane and in the cloudy regions, the ratio of spatial densities of dusty ρ_d and gaseous ρ_g matter being $\rho_d/\rho_g \sim 0.01$ in the average (see e.g. Greenberg and Hong, 1975; Spitzer, 1981). At the same time there are observational data indicating the presence of high-velocity (70-300 km s^{-1}) objects and corresponding high-velocity dust grains in the Galaxy. For example, the relative velocities of high-velocity clouds (HVC's) and the disk of our Galaxy have such values at their possible collisions (see e.g. Giovanelli, 1980; Mirabel and Morras, 1984; Dickey and Hailes, 1985; Tenorio-Tagle et al., 1987 and references therein).

High-velocity collisions also occur in the interplanetary and circumsolar medium between cometary and zodiacal dust particles. During high relative velocity ($V \geq V_1 = 70$ km s^{-1}) impacts of dust grains high-density high-temperature plasma balls (initial density and temperature of balls are $n_{io} \simeq 10^{22}$ ion cm^{-3} and $T_o \geq T_{o1} = 3\ 10^5$ K) and X-ray radiation may be generated both in the cometary atmospheres and in the interstellar medium (Ibadov, 1980; 1981).

The present report is devoted to theoretical consideration of the efficiency of conversion of colliding high-velocity dust grains kinetic energy into X-ray radiation related to the origin of the diffuse soft cosmic X-ray background.

2. X-ray generation by high-velocity collisions of grains

High-velocity collisions between dust grains of interstellar type, having radii $a \geq 10^{-6}$ cm, are passing the stage of fully thermalization of the kinetic energy of their relative motion as the calculation of the atomic particle transport length shows. During such impacts specific powers of the order of 10^{12}-10^{15} W cm^{-2} are developed and a hot expanding plasma ball with the initial radius $r_o = a$ is generated. The comparison of the time for balance of electron and ion temperatures τ_b (Artsimovich, 1961; Spitzer, 1965) and the characteristic time for the plasma ball radiative cooling τ_r with the characteristic ball's expansion time τ_e shows that $\tau_b < \tau_e < \tau_r$, so that the arising plasma is quasi-isothermal and its expansion is quasi-adiabatical.

Since plasma balls produced consist of heavy ions of C, N, O, Si, Mg, Fe etc. with the average atomic number $Z \simeq 10$ and the mean multiplicity of charge $z \geq 3$ at $V \geq V_1$ (Ibadov, 1986), the main contribution to the luminosity of plasma balls is supplied (at $T_o \leq 3\ 10^5 Z^2$, K) by recombinational radiation (free-bound transitions) and by emission of excited ions (Artsimovich, 1961; Ginzburg, 1962; Lang, 1978).

The energy, emitted in the X-ray range by a radially expanding plasma ball, is determined as

$$E_x(fb) = 10^{-21} g_{fb} z^4 \int_0^{\tau_x} n_e n_i T^{-1/2} V_p \, dt \quad \text{for } r_o < l_\nu(fb); \quad (1)$$

$$E_x(bb) = \int_0^{\tau_x} \sigma T^4 S \, dt \quad \text{for } r_o \geq l\ (fb). \quad (2)$$

Here τ_x is the hot plasma ball life-time; $l_\nu(fb)$ is the mean free path of plasma photons for free-bound transitions; g_{fb} is the Gaunt factor for electron free-bound transitions; $n_e \equiv n_e(r)$ and $n_i \equiv n_i(r)$ are the number densities of plasma electrons and ions; $T = T(r)$ is the plasma ball temperature; $r \equiv r(t)$ is the radius of plasma ball: the time $t=0$ corresponds to $r = r_o$; $V_p \equiv V_p(r)$ and $S \equiv S(r) = 4\pi r^2$ are the volume and the surface of the plasma ball; σ is the Stefan-Boltzman constant; the Eq.(1) corresponds to radiation of an optically thin plasma ball and the Eq.(2) - to optically thick plasma (black-body radiation); values are in CGS system.

The spatial-temporal variation of parameters in Eqs. (1) and (2) is determined by the following equations

$$-\frac{3}{2}(N_e+N_i)\frac{k\,dT}{dt} = \frac{(N_e m_e+N_i m_i)}{2}\frac{d}{dt}\left(\frac{dr}{dt}\right)^2 , \tag{3}$$

$$(n_e+n_i)kT\frac{dV_p}{dt} = \frac{(N_e m_e+N_i m_i)}{2}\frac{d}{dt}\left(\frac{dr}{dt}\right)^2 , \tag{4}$$

where N_e and N_i are the total numbers of electrons and ions in the plasma ball, k is the Boltzman constant, m_e and m_i are the mass of electron and the mean ion mass.

The equation of energy conservation (3) and the equation of motion of the plasma volume as a whole (4) are complemented by following relations

$$V_p = (4\pi/3)r^3, \quad n_e = zn_i, \quad n_i = 3N_i/(4\pi r^3); \tag{5}$$

$$T_o = \frac{Am_h V^2}{12k(1+z+2x_1/3)} ; \tag{6}$$

$$z = \begin{cases} z_1(V/V_1)^{2/s_1} & \text{for } V \le V_z; \\ Z & \text{for } V \ge V_z, \end{cases} \tag{7}$$

where A is the mean mass number of atoms in colliding particles, m_h is the mass of hydrogen atom, x_1 is the mean relative energy of ionization; $z_1=3$, $1 \le s_1 \le 2$, $V_z=2\ 10^6 Z$ is the minimal relative velocity of colliding dust grains at which the charge of produced ion equals to charge Z of atomic nucleus (Ibadov, 1986).

From Eqs. (3) and (4), taking into account Eq. (5), we obtain the law of variation of the temperature and radius of the ball in the form

$$T = T_o(r_o/r)^2, \tag{8}$$

$$r^2 = r_o^2+2r_oV_{ro}t+V_a^2t^2. \tag{9}$$

Here $V_{ro} \equiv (dr/dt)_{r=r_o} = (kT_o/2\pi m_i)^{1/2}$ is the initial radial velocity of ions in plasma ball, $V_a \equiv [V_{ro}^2+3(1+z)kT_o/m_i]^{1/2}$ is the asymptotic velocity of expansion of the ball.

Since $V_{ro} \ll V_a$, during the time $t=r_o/V_a$ the ball temperature decreases, according to Eqs. (8) and (9), up to $T=T_o/2$, so that the X-ray emission pulse from the ball has the duration $\tau_x = r_o/V_a$.

Inserting into Eqs. (1) and (2) relations (5), (8) and (9) after integrating we have

$$E_x(fb)=2.8\ 10^{-25} g_{fb} Z^{1/2} z^5 n_{io}^2 r_o^4/(1+z)^{1/2} T_o \quad \text{for } r_o<l_\nu(fb); \tag{10}$$

$$E_x(bb)=3.5\ 10^{-8} Z^{1/2} T_o^{7/2} r_o^3/(1+z)^{1/2} \quad \text{for } r_o\geq l_\nu(fb). \tag{11}$$

The kinetic energy of relative motion of two colliding dust grains, expenditured for creating the hot plasma ball, may be presented as

$$E_{in}=(\pi/3) m_p Z n_{io} r_o^3 V^2, \tag{12}$$

where m_p is the proton mass, n_{io} is the initial plasma ions density.

Using Eqs. (10)-(12) we get the efficiency of conversion of kinetic energy of colliding dust grains into X-ray radiation $k_x=E_x/E_{in}$, namely

$$k_x = \begin{cases} 0.17 g_{fb} z^5 n_{io} r_o/\left[(1+z)Z\right]^{1/2} T_o V^2 & \text{for } r_o<l_\nu(fb); \\ 1.8\ 10^{16} T_o^{7/2} / \left[(1+z)Z\right]^{1/2} n_{io} V^2 & \text{for } r_o\geq l_\nu(fb). \end{cases} \tag{13}$$

It should be noted that the expression for $l_\nu(fb)$ may be be obtained by equating the volume and the surface luminosities - the expressions (10) and (11), at the case of equality of the plasma ball dimension r_o and the mean transport length of photons $l_\nu(fb)$.

Accepting $V=1.5\ 10^7$ cm s^{-1}, $s_1=2$, $x_1=3$, $g_{fb}=1$ and $n_{io}=3\ 10^{22}$ ion cm^{-3} (corresponds to the values of $A=2Z=20$ and of the density of dust grain $\delta=1$ g cm^{-3}) we have $z=6$, $T_o=6\ 10^5$ K, $l_\nu(fb)=3\ 10^{-6}$ cm and by the lower line of Eq. (13) we get $k_x=k_x(bb)=0.1$. This value corresponds to the black-body emission of the optically thick plasma, produced by the interstellar dust grains ($a\simeq10^{-6}-10^{-5}$ cm), and the most probable energy of photons emitted is $h\nu_m \simeq 3kT_o \simeq 200$ eV; the value of $k_x=0.01$ was used in calculations earlier fulfilled (Ibadov, 1981), which corresponds to the Bremsstrahlung radiation mechanism (free-free transitions) of electrons in the hot optically thin deyterium plasma, produced by picosecond laser pulses (see Basov et al., 1971).

The intensity of the diffuse soft X-ray radiation due to high-velocity collisions of HVC's dust particles with dust grains of the disk of our Galaxy near the zone of interaction may be presented as

$$J_x = (1/8) k_x \rho_{dp} V^3, \tag{14}$$

where ρ_{dp} is the spatial density of dusty component transforming into hot plasma balls.

The observed value of soft X-rays intensity $J_x = 10^{-8}$ erg cm^{-2} s^{-1} is reached according to Eqs.(13) and (14) at $\rho_{dp} = 3\ 10^{-28}$ g cm^{-3}. Hence, if the density of gas in the HVC is $\rho_{gc} = 10^{-25}$ g cm^{-3} and the ratio of densities of dust ρ_{dc} and gas ρ_{gc} in the cloud $\rho_{dc}/\rho_{gc} > 0.01$, the HVC with dimensions $r_c \lesssim 30$ pc may give appreciable contribution to the diffuse soft cosmic X-rays within distances r = 100 pc considered (see also Ibadov, 1981; Hirth, Mebold and Müller, 1985).

3. Conclusion

Interstellar dust grains high-velocity collisions (70-300 km s^{-1}) result in generation of dense hot plasma balls ($3\ 10^5$-$5\ 10^6$ K) of heavy elements (C, N, O, Si, Mg, Fe etc.), which cause relatively high efficiency of conversion of grains kinetic energy into X-ray radiation at the cost of recombination and line emission mechanisms.

High-velocity collisions between the dusty components of high-velocity clouds and of the disk of our Galaxy may be one of the alternative processes responsible for creating the observed distribution of diffuse component of soft cosmic X-rays in the energy range 0.1-1 keV.

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References

Apparao, K.M.V., Hayakawa, S. and Hearn, D.R.: 1979, Astrophys. Space Sci. 65, 419.

Artsimovich, L.A.: 1961, Controlled Fusion, Fizmathgiz, Moscow.

Basov, N.G., Zakharov, S.D., Krokhin, O.N., Kryukov, P.G., Senatsky, Yu.V., Tyurin, E.L., Fedosimov, A.I., Chekalin, S.V. and Shchelev, M.Ya.: 1971, Quantum Electronics USSR, No. 1, 4.

Castor, J., McCray, R. and Weaver, R.: 1975, Astrophys. J. Letters 200, L107.

Cox, D.P. and Smith, B.W.: 1974, Astrophys. J. Letters 189, L105.

Ginzburg, V.L.: 1962, Proc. P.N. Lebedev Phys. Inst. USSR Acad. Sci. 18, 55.

Giovanelli, R.: 1980, Astron. J. 85, 1155.

Greenberg, J.M. and Hong, S.S.: 1975, The Dusty Universe, N. Watson Academic Publ., New York.

Hirth, W., Mebold, U. and Müller, P.: 1985, Astron. Astrophys. 153, 249.

Ibadov, S.: 1980, Comet Circular USSR No. 266, 3.

Ibadov, S.: 1981, Proc. 15th Internat. Conf. on Phenomena in Ionized Gases, Minsk, USSR, v. 1, p. 265.

Ibadov, S.: 1986, Proc. 20th ESLAB Symposium on Exploration of Halley's Comet, Heidelberg, FRG: ESA SP-250, v. 1, p. 377.

Kaplan, S.A. and Pikelner, S.B.: 1979, Physics of the Interstellar Medium, Nauka, Moscow.

Kulkarni, S.R., Dickey, J.M. and Heiles, C.: 1985, Astrophys. J. 291, 716.

Lang, K.R.: 1978, Astrophysical Formulae, v. 1, Mir, Moscow.

Mirabel, F.I. and Morras, R.: 1984, Astrophys. J. 279, 86.

Spitzer, L., Jr.: 1965, Physics of Fully Ionized Gases, Mir, Moscow.

Spitzer, L., Jr.: 1981, Physical Processes in the Interstellar Medium, Mir, Moscow.

Syunyaev, R.A.(ed.): 1986, Physics of the Space, Soviet encyklopaedia, Moscow.

Tanaka, Y. and Bleeker, J.A.M.: 1977, Space Sci. Rev. 20, 815.

Tenorio-Tagle, G., Franco, J., Bodenheimer, P. and Rozyczka, M.: 1987, Astron. Astrophys. 179, 219.