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Modeling of the Dust Tail of Comet C/2012 S1 (ISON) from the Results of Observations

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Abstract—The results of the dynamic modeling of the process, that formed the dust tail of comet C/2012 S1 (ISON), are presented. The images of the comet were acquired with the 1-meter Zeiss-1000 telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS). To construct the model of the dust tail, the trajectories of 50 million dust particles were traced. The distribution of brightness in the dust tail of the comet was reproduced in the model. According to our model investigations, the observed tail could be formed by dust particles with the sizes ranging from 0.5 to 16.6 μm and the escape velocities from 17 to 130 m/s; the power exponent of the distribution by radius is –2.5, and the maximum age of the dust particles having formed the cometary tail is 25 days. In the paper, the brightness of the comet at the moment of observations is also estimated, and the morphology of the cometary coma is analyzed with the use of digital filters.

Keywords: comet C/2012 S1 (ISON), cometary dust tail, cometary coma morphology

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INTRODUCTION

To understand the evolution of the Solar System, it is important to study the nature of comets. Since comets dwell on the periphery of the Solar System, where the radiation field is weak, they contain the primary material that remained from the time of the Solar System formation. Because of this, the investigations of dynamically new comets, that appear in the inner part of the Solar System for the first time, may yield new information on the physical conditions of their formation and the properties of their dust and gas.

A dynamical new comet C/2012 S1 (ISON) was discovered by Nevskii and Novichonok on September 21, 2012, with the use of the 0.4-m telescope operating within the International Science Optical Network in Russia (Novski et al., 2012). The activity of the comet was first noticed at the heliocentric distance of 10 AU (Cochran, 2014). The comet is classified as originating from the Oort cloud; its eccentricity is $e = 1.000004$, and the orbit inclination is $i = 62.4°$ (Williams, 2013). The comet passed the perihelion on November 28, 2013, at a distance of 0.0125 AU and, having completely lost volatile material, did not survive the approach to the Sun and was not observed after perihelion. The modeling of the cometary tail at perihelion and the problem of fragmentation and disintegration of the cometary nucleus are considered in the paper by Sekanina and Kracht (2014).

Since the comet was observed both in the zone, where the water ice sublimation is insignificant, and in the zone where water ice sublimation is already responsible for the material entrainment from the surface of the cometary nucleus, the evolution of its activity and the changes of the dust properties and chemical composition in different wavelength ranges could be studied. From the review of the currently available data on the comet, several important results can be noted. The analysis of the light curve of the comet for the whole observational period has revealed that the activity of the comet was a flare and unpredictable character and that the disintegration of the comet most likely started even before the perihelion (Sekanina and Kracht, 2014). The behavior of the light curve itself is typical of the Kreutz family comets observed from the SOHO and STEREO spacecraft (Knight et al., 2013; Curdt et al., 2014).

Concerning the gas production rate of H_2O, its maximum value of 2×10^{30} molecule/s was detected five days before the perihelion. The spectral data yielded that the comet was depleted of such compounds, as CH_3OH, C_2H_6, and CH_4, and enriched with NH_3, while it showed a typical content of C_2H_2 and CHN (Dello Russo et al., 2014). Moreover, observations of the comet at heliocentric distances from 1.2 to 0.3 AU showed that the CO content was rather constant, while the H_2CO content gradually changed from the depleted state to the increased one at perihelion (Dello Russo et al., 2014; Disanti et al., 2014).

From the results of observations of the comet carried out in the infrared range at the heliocentric distance of 1.15 AU within the frames of the SOFIA (Stratospheric Observatory for Infrared Astronomy) project, it was obtained that the particles from 0.7 to 1 μm in size dominated the cometary coma (Wooden et al., 2014).

In the present paper, the results of the modeling of the dust tail of comet C/2012 S1 (ISON) are reported. In addition to the reproducing of the cometary dust tail in the model, the morphology of the coma and tail of the comet was studied with the use of digital filters. The apparent and absolute stellar magnitudes of the comet were also estimated.

OBSERVATIONS AND IMAGE PROCESSING

Photometric observations of comet C/2012 S1 (ISON) were performed before its perihelion passage with the 1-meter Zeiss-1000 telescope at the Special Astrophysical Observatory (SAO RAS) on October 11, 2013. The comet was at a distance of 1.45 AU from the Sun and 1.85 AU from the Earth. The CCD matrix EEV 42-40 with 1044 × 1046 pixels was used as a radiation receiver. In the 2 × 2 binning mode of the instrument, the size of the acquired images and the scale were 8′ × 8′ and 0.476″ per pixel, respectively.

The images were obtained in the wideband *BVRc* filters. These filters rather closely reproduce the bands of the Johnson-Cousins photometric system. In the *R*c, *B*, and *V* filters, 8, 8, and 5 images were obtained, respectively; their exposures were from 30 to 60 s, from 30 to 120 s, and 30 s, respectively. The twilight morning sky was observed as flat fields. To obtain the absolute photometric values, the images of the PG1657+078 star field (Landolt, 1992) were made on the same night. The spectral dependence of the transparency coefficient for the terrestrial atmosphere was taken from the paper by Kartasheva and Chunakova (1978).

For the standard reduction of CCD frames, the master-frames of the electron shifting and flat field were produced. All of the frames with the images of the comet and standard stars were corrected for the zero-point and for the inequality of the pixel sensitivity with the use of the master-frames. The sky background was determined with the "sky" subroutine of the IDL library (Landsman, 1993).

All of the frames were reduced to a common centre, corresponding to the coordinates of the image of the comet in one of the frames, and summed up. The obtained set of the frames was used for modelling the dust tail, estimating the brightness of the comet, and isolating the structures in the cometary coma.

THE COMETARY BRIGHTNESS ESTIMATE

The stellar magnitudes of comet C/2012 S1 (ISON) in the *B*, *V*, and *R*c filters measured with the aperture of the 30″ radius were 14.1 ± 0.03, 13.6 ± 0.01, and 12.7 ± 0.01, respectively. To calculate the error in the stellar magnitude, we summed up the statistical errors caused by the *S*/*N* ratio for the comet and reference stars, the errors in the estimates of the atmospheric transparency coefficient, and the errors in the catalogue magnitudes of the star standards.

We also derived the absolute stellar magnitude of the comet in the *R*c filter from the expression

$$m_R(1,1,0) = m_R - 5\log(r\Delta) - \Phi(\alpha),$$

where r and Δ are the heliocentric and geocentric distances expressed in astronomic units, respectively, and $\Phi(\alpha)$ is the phase function, where $\alpha = 32.4°$ is the phase angle of the comet.

The absolute stellar magnitude of 9.2 ± 0.01 was obtained for the comet. This value agrees with the analogous estimate found for the heliocentric distance of 1.45 AU by Sekanina and Kracht (2014).

MODEL

To reproduce the dust tail of comet C/2012 S1 (ISON) in simulations, the model developed by Korsun et al. (2010) for the analysis of dust tails of distant comets with perihelion distances larger than 4 AU was used. The suggested model is based on the statistical Monte-Carlo method (Cashwell and Everett, 1959). In the model, the motion of particles with variable masses is considered; the particles are assumed to be composed of a silicate core surrounded by an organic component and covered by a water-ice mantle with carbon inclusions.

In our case, to analyze the dust tail of comet C/2012 S1 (ISON), which was relatively close to the Sun (1.45 AU on October 11, 2013), we took into account that the ice component of particles had completely sublimated and the motion of strongly porous refractory particles is to be considered. Such a version of the model has been already applied to the dust tails of comets C/1995 O1 (Hale-Bopp) and C/2006 P1 (McNaught) that were also observed at small heliocentric distances (Kharchuk et al., 2009; Kharchuk and Korsun, 2010).

To model the dust atmosphere of the comet, the trajectory of each of the dust particles is traced from the collision zone surrounding the nucleus to the moment of the observation. The trajectories of the particles that left the collision zone are controlled by the solar gravity and solar radiation pressure. The motion of particles is considered in the noninertial cometocentric coordinate system {ξ, η, ζ}, and the

Model parameters of dust in comet C/2012 S1 (ISON)

Model parameter	Values
Maximum age of dust particles	25 days
Radii of dust particles	0.5–16.6 μm
Degree of distribution law for size	–2.5
Velocity of dust particles	17–130 m/s

system of motion equations can be presented in the following way (Chörny, 2005; 2007)

$$\ddot{\xi} = \mu_s(1-\beta)\frac{r+\xi}{y^3}\mu_c\frac{\xi}{x^3} - \ddot{\theta}\eta - \dot{\theta}^2\xi - 2\dot{\theta}\dot{\eta} - \mu_s\frac{1}{r^2},$$

$$\ddot{\eta} = -\mu_s(1-\beta)\frac{\eta}{y^3} - \mu_c\frac{\eta}{x^3} - \ddot{\theta}\xi + \dot{\theta}^2\eta - 2\dot{\theta}\dot{\xi},$$

$$\ddot{\zeta} = -\mu_s(1-\beta)\frac{\zeta}{y^3} - \mu_c\frac{\zeta}{x^3},$$

where $\mu_s = Gm_s$ is the solar gravity parameter; $\mu_c = Gm_c$ is the gravity parameter of the comet; r, $\dot{\theta}$, and $\ddot{\theta}$ are the heliocentric distance of the comet, its angular velocity, and its angular acceleration relative to the Sun, respectively; $x = \sqrt{\xi^2+\eta^2+\zeta^2}$ and $y = \sqrt{(1+\xi)^2+\eta^2+\zeta^2}$. The cometocentric coordinate system originates from the center of the cometary nucleus. The ξ and η axes are coordinates of the plane of the cometary orbit, where the ξ axis is radially directed to the Sun and the η axis determines the heliocentric velocity vector of the comet taken with a negative sign. The third axis ζ is perpendicular to the plane of the cometary orbit.

An additional model equation describes the rate of the change of the particle size due to sublimation:

$$\frac{da}{dt} = \frac{\mu m_p}{\rho}p_v\frac{1}{\sqrt{2\pi\mu m_p kT}},$$

where μ is the molecular weight of the sublimating molecules, m_p is the atomic mass unit, k is the Boltzmann constant, T is the temperature of the particle, and p_v is the saturation vapour pressure of the volatiles. In the model analysis of the tails of comets that are close to the Sun, it is assumed that $da/dt = 0$.

To calculate the equations with the Monte-Carlo algorithm, the time and the direction of the escape of a dust particle are specified. The other model parameters are also assumed: the radius of a dust particle, the velocity of its escape from the collision zone, the maximum age of the dust particles that can form the tail, and the power exponent γ of the size distribution of dust particles $n(a) = \alpha^{\gamma}$. The maximum age of particles is determined from the optimal set of the model parameters providing the agreement between the isophots in the modeled and observed images. The solution of the system of equations yields the coordinates of a dust particle at the observation moment, and the array of these coordinates forms the model of the dust tail of the comet. To be compared to the observational data, the obtained cometocentric coordinates of dust particles are projected onto the sky plane.

The escape velocities of particles were determined with the empiric formula suggested by Sekanina et al. (1992)

$$V = r_{\rm d}^{-0.5}/(A + Ba^{0.5}).$$

Here, V is the escape velocity of dust particles, A and B are numerical parameters, $r_{\rm d}$ is the heliocentric distance of a dust particle, and a is its radius. In the present modelling, the volume density of particles was assumed at $\rho = 1$ g/cm^3.

MODELLING PROCEDURE AND DISCUSSION OF THE RESULTS

The modeling was carried out with the computer code written in the Fortran programming language. To start computations and control the results, the IDL software package dealing with the image analysis was used. As a criterion of the agreement between the observed and modeled data, the fitting degree of the sets of isophots was chosen. For convenience, the values of all of the model parameters were collected in a separate file.

The modeled image was compared to the observed one that was obtained on October 11, 2013. The modeled image of comet C/2012 S1 (ISON) was formed by 50 million particles. The source of dust particles was a sunward cone with an opening angle of 100°. The modeling yielded the optimal model parameters (the radii of dust particles, their velocities, the maximum age, and the power exponent of the size distribution $n(a) = a^{\gamma}$) that characterize the dust component of the cometary atmosphere. The values of the model parameters are listed in the table.

The results of the modeling are illustrated with a pair of the modeled and observed images shown side by side in Fig. 1 and with the sets of isophots compared in Fig. 2.

INVESTIGATIONS OF THE STRUCTURES IN THE COMETARY COMA

Comet C/2012 S1 (ISON) demonstrated the substantial jet activity both at the heliocentric distances larger than 4 AU and at the distances closer to the perihelion (Li et al., 2013; Knight et al., 2013; Scarmato, 2014). At large heliocentric distances, the comet was observed from the HST (Hubble Space Telescope) spacecraft (Li et al., 2013), and the morphology of the comet was also studied from the obtained images. A jet with an opening angle of about 45° was found in the comet at the position angle of 291°. This structure was also detected in the ground-

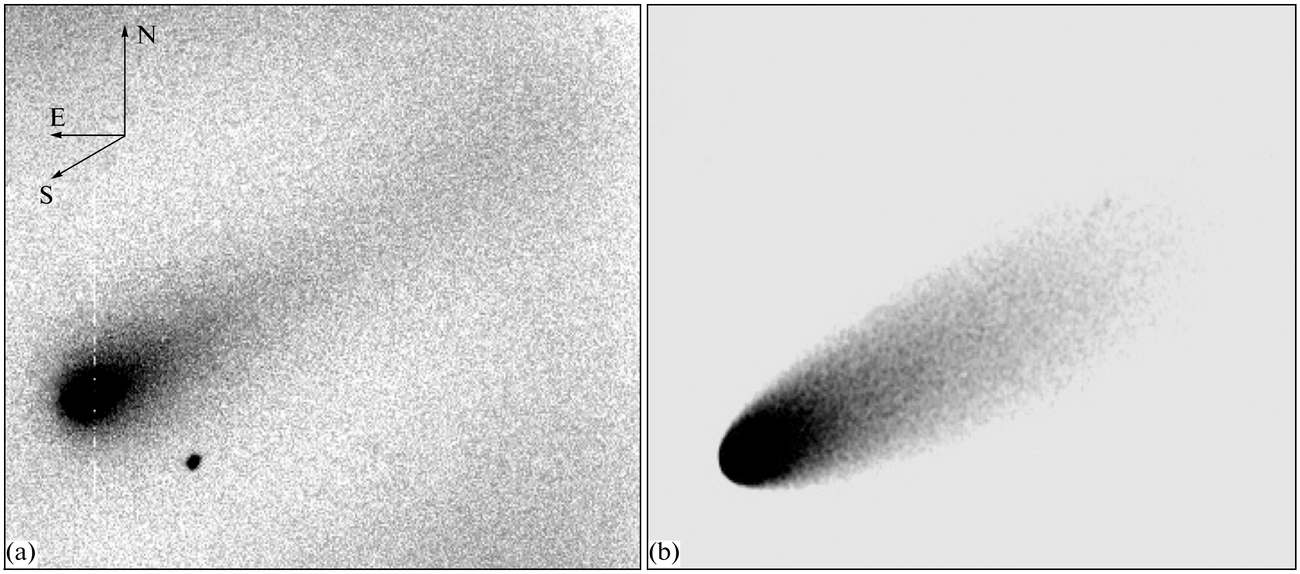

Fig. 1. The results of the modeling of comet C/2012 S1 (ISON). The modeled image of the comet (b) is on the right of the observed image (a).

based observations, though with a lower spatial resolution; it was kept relatively invariable from March to May 2013 (Knight et al., 2013).

Application of the digital filters and the 1/ρ model to the ground-based observations of comet C/2012 S1 (ISON) carried out from October to November, 2013, also revealed the presence of jet structures in the cometary coma (Scarmato, 2014). Our observations of the comet were also made in this period. Because of this, to search for the weak-contrast structures in our images and to isolate them, we used a digital filtering technique.

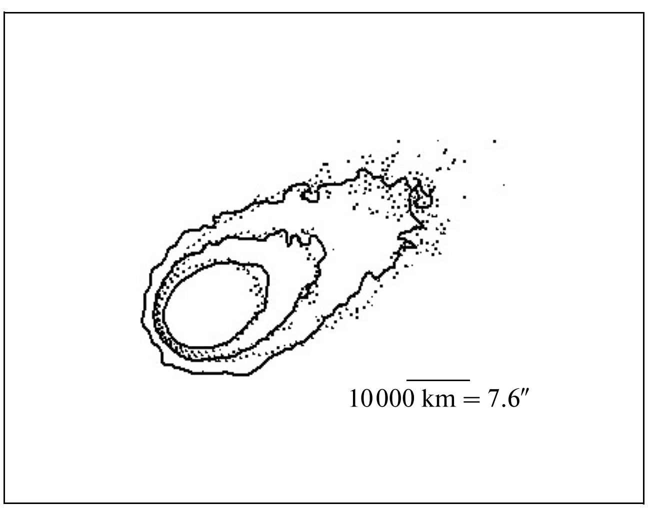

Fig. 2. The results of the modeling of comet C/2012 S1 (ISON). The modeled set of isophots (dots) is compared to the observed one (solid curves).

To distinguish the low-contrast structures in the images of the dust coma of comet C/2012 S1 (ISON), we used the Astroart software containing a number of digital filters (http://www.msb-astroart.com/). The morphology of the comet was studied with the isolating technique that had been earlier used for comets C/2002 C1 (Ikeya-Zhang) (Manzini et al., 2007), Schwassmann-Wachmann and C/2003 WT42 (LINEAR) (Korsun et al., 2008; 2010; Ivanova et al., 2012), and C/2012 S1 (ISON) (Scarmato, 2014) and yielded good results. The used filters are described in more detail by Ivanova et al. (2012).

Figure 3 presents the summarized image in the *R*c filter and the structures isolated in the coma with the digital filters. The structure (jet) directed to the Sun can be seen.

The analogous structure can be seen in the processed images of October 15, 2013, presented in the paper by Scarmato (2014).

MAIN RESULTS

Cremonese and Fulle (1990) and Fulle et al. (1992) suggested that it is worth searching for the correlation in the dust properties between the long-period comets and the dynamic new comets that appear in the inner parts of the Solar System for the first time. The data available in the literature on the comparison of the comets of different types showed that the power exponent of the size distribution of particles in the long-period and dynamic new comets is substantially higher (from –3.0 to –3.5) than that in the long-period comets (from –3.6 to –3.8). From the data of our modeling for the dynamic new comet C/2012 S1 (ISON), it was found that the power exponent of the size distribu-

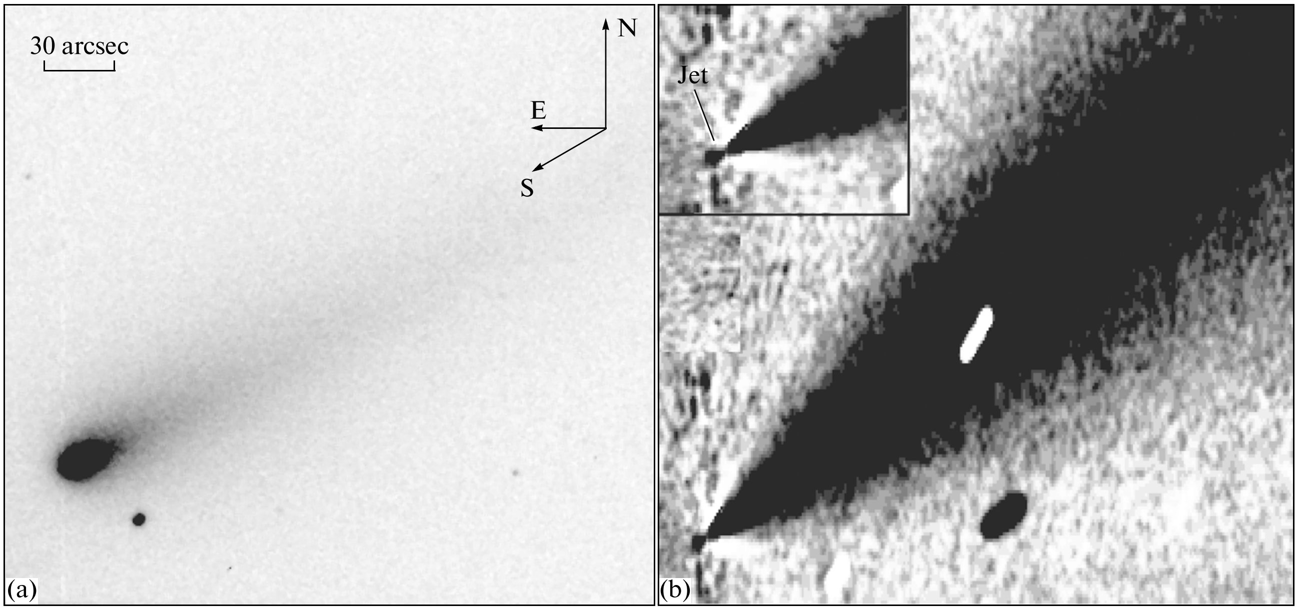

Fig. 3. The image of comet C/2012 S1 (ISON) acquired in the *R*c filter (a) and the image of the comet after processing with digital filters (b). The directions to the North (N), the East (E), and the Sun (S) are indicated.

tion of its dust particles is even higher, –2.5. Such power exponent points to the increase of a portion of large particles in the cometary tail. The power exponent determined here for comet C/2012 S1 (ISON) correlates with the estimates of the power exponent obtained earlier for comets D/1993 F2 Shoemaker-Levy-9 (Hahna and Rettig, 2000) and 1P/Halley (Mazets et al., 1986). Moreover, according to the estimates reported by Vincent et al. (2010), the power exponent may vary from –2.5 to –3.0 for dust grains with sizes from one micron to one millimeter. The measurements of dust fluxes carried out during the spacecraft passages near the nuclei of comets 1P/Halley (*Giotto*) and 81P/Wild 2 (*Stardust*) showed the presence of the particles with equivalent radii from nanometers to millimeters; they are described by the size distribution law with the power exponent varying from –2 to –4 in dependence of the sizes and location in the cometary coma (Kolokolova et al., 2010).

The estimated radii of the dust particles that form the dust tail of the comet are within the range from 0.5 to 16.6 μm, which agrees with the estimates of the sizes of dust particles obtained for this comet by Wooden et al. (2014).

The velocities determined in the present modeling, from 17 to 130 m/s, agree with the estimate of the velocity of the dust emitted from the crater artificially produced in comet 9P/Tempel during the *Deep Impact* mission. At that time, the comet was at a distance of approximately 1.5 AU; and the dust velocities after the dust-gas interaction reached the values ranging from 10 to 600 m/s with the Gaussian maximum at about 190 m/s (Jorda et al., 2007).

In their turn, the results of simulations of the dust tails for dynamically new comets C/1995 O1 (Hale-Bopp) and C/2006 P1 (McNaught) showed that the power exponent of the size distribution of dust particles averages from –3.6 to –3.5, which corresponds to its upper limit for the long-period comets and its lower limit for the short-period comets (Kharchuk et al., 2009; Kharchuk and Korsun, 2010).

At the moment of observations, the spectrum of the comet demonstrated a number of emissions in the visible range (DiSanti et al., 2014); due to this, to reliably estimate the color and the dust production rate, we could not use the images obtained in the wideband *BVR*c filters. From the acquired data, we estimated the absolute stellar magnitude of the comet at the observation moment as $9.2^m \pm 0.01$, which agrees with the results reported in the literature.

The morphology of the cometary coma was studied. With the digital filters and the method of eliminating the low-frequency trends, we succeeded in distinguishing the structure. In the images obtained on October 11, 2013, the sunward jet was isolated, which agrees with the results described in the literature and confirms the substantial flare activity of the comet near the perihelion.

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