Which celestial bodies are associated with the meteors ?

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Introduction

The intent of this report is to tie up the possible sources of meteorites. Formerly the comets were considered as the vast source of the observable meteors but the evolution and improving knowledge about the comets especially their nuclei arised the doubt that many of meteorites which were found and analyzed in the laboratories cannot be originated from the comets. The obvious other suspicious objects which can be as source bodies of the meteoroids and meteorites are the asteroids. Consequently, aside from the comets there are various other sources and possible parent bodies of the meteoroids as Main Belt (MB) asteroids or near Earth environment (Near Earth Asteroids NEAs). The near Earth space enviroment contains complex swarm of objects as the objects in the Taurid–Encke Complex which consist of both asteroidal and cometary objects as well as meteoroid streams, so the Near Earth Objects (NEOs) can be as another major source of the meteoroids. This report attempts to highlight the major sources of the meteoroids without any completeness because the complete inventories can be found in the literature [1].

Dust, meteoroid, meteor, meteorite

The small scale solid material in the Universe (in the Solar System and beyond) are the cosmic dust particles and meteoroids. It is worth-while to distinghuish them from each other. The distinction is mainly based on the size differences. The *dust* is the solid particulate material with sizes less than 100 microns. For example the dust grains form the interplanetary dust, circumplanetary dust (as planetary rings, for instance), circumstellar dust around the stars, and interstellar dust. The cosmic spherules, microtektites, aggregate complex dust grains, and sub-micron dust condensates also belong to the dust-sized particle category. A *meteoroid* is a celestial body with a size ranges from 100 microns to 100 meters. These orbit either around the Sun, major planet, planetary satellite, any small body as cometary nucleus, asteroid or move in the interstellar or intergalactic space. Some small asteroid can belong to this category according to its size. Some examples for a meteoroid as follows: 1998 KY26 a small Near Earth Asteroid with a diameter of 30 m observed by radar. Possibly the body related to the Tunguz–phenomena in 1908 had a 70 or maximum a 100 meters object in size. The *meteor* is an event which can be observed during the interaction of the meteoroid body entering to the atmosphere of a given planet. It is possible that the encouner between a planet and a meteoroid has a grazing incidence angle and the meteoroid can continue its path but the orbit is usually canged (e.g., Grand Teton daytime bolide in 1972). The by-products of a meteor event could

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[1] This communication is a short synthesis based on the works done (in alphabetic order) by D. Asher, W. Baggaley, P. Babadzhanov, M. Beech, R. Binzel, J. Burns, Z. Ceplecha, S. Clube, D. Dunham, P. Farinella, M. Gaffey, M. Gavajdova, M. Greenberg, R. Greenberg, E. Grün, B. Gustafson, M. Hanner, I. Hasegawa, A. Harris, J. Hartung, T. Hayward, P. Jenniskens, E. Jessberger, J. Klacka, Z. Knezevic, L. Kresak, P. Lamy, M. Lazarrin, A. Li, D. Lynch, H. McSween, F. Migliorini, A. Milani, A. Morbidelli, V. Nemtchinov, M. Nolan, J. Ortiz, D. Rabinowitz, D. Steel, V. Shuvalov, A. Taylor, I. Toth, P. Warren, I. Williams, V. Zappala, V. Ziolkowski.

be spherules which are the spray-like solid (usually glassy) condensates created during the high-temperature process and they fall down slowly reaching either the ground or the surface waters (lakes, rivers, seas, and oceans). If a meteoroid collide with an atmosphereless body the phenomena is called as impact or collision event. Sometimes the high velocity collisons create cosmic spherules (e.g. tektites, microtektites). A *meteorite* is a recoverable definite relict body of a meteoroid which survived the interaction with the atmosphere of a planet or the collision process with an atmosphereless celestial body. This can be found and collectable either from the ground or surface waters (lakes, rivers, seas, and oceans) and it can be analyzed in laboratories.

Nowadays it is more precise to mention "meteoroid stream" instead of "meteor stream". However, the formerly used "meteor stream" is frequently used in the literature because it is commonly known by everybody without any misunderstanding about their orbital motion and physical nature.

Sources of the meteoroids

There are sources of Solar System dust and meteoroids relating to the bodies both inside the Solar System and beyond.
The brief inventory of the types of celestial bodies as the dust and meteoroid sources in the Solar System including the meteoroids in the near Earth space are the following:

- comets (short- and long–period: Earth Crossing Comets. E.g., the comet 2P/Encke is a permanent vast source of dust and meteoroids in the inner Solar System as a member of the Taurid–Encke Complex.
- asteroids (Main Belt asteroids, NEAs).
- planetary satellites (e.g., Moon: meteoroids, tektites; Io: volcanic ejecta; dust in the Martian environment: Phobos, Deimos).
- tidal disrupted bodies due to the tidal effect of major planets (e.g., fragments of the comet D/Shoemaker–Levy 9; dust rings; formerly disrupted NEOs by Earth or other major planets).
- major planets: impact ejecta material delivered to an interplanetary orbit and falled to another planet (SNC meteorites from Mars to Earth). Impact ejecta from large crater forming events (from the Earth: K/T event).
- debris material due to the mutual collisions of small bodies (e.g., asteroid–asteroid, comets–meteoroid swarms, meteoroid–meteoroid, dust grains – dust grains). Recent collisions in the outer Solar System: transneptun objects as the dust and meteoroid sources. Oblique impacts, jetting, grazing impacts: meteoroids, spherules, dust.
- Dust–condensation in the solar atmosphere (?). Circumsolar dust.

Dust and meteoroid sources beyond the Solar System:

- Post–AGB stars: dust–condensation in their atmosphere and stellar wind driven dust.
- Dust from the atmosphere of A-type stars at certain location in HRD: e.g., β Pic, HR 4796, 49 Cet; and IR sources at λ: 11.7, 18.7 μm.

- Strong stellar winds from other type of stars.
- Dust driven by the interaction between a star and the interstellar material.
- Other interstellar dust: supernova shock drives the interstellar dust.

Orbital delivery services

How these meteorites got from their parent bodies to the Earth ? However, the mechanisms by which samples are liberated from their parent bodies and the routes by which they find their way to Earth can be analized indirectly: either by methods of the celestial mechanics as orbit determination, perturbation analysis, types of resonances etc. or empirically as photometry and observations of spectra of the possible parent bodies, laboratory analysis of meteorites (chemical composition, age determination, studying the consequences of cosmic–ray exposure etc.).

It is not possible to follow precisely the route of any particular meteoroid in the space during its entire Odyssey, altough the orbits at the interval of interacting with the terrestrial atmosphere can be calculated observing their path. Sometimes the plausible paths from the parent bodies to Earth can be reconstructed.

The initial conditions in the motion of the meteoroids are usually unknown and these are affected by the time instant and location of the ejection event from the parent body, the initial velocity (acceleration processes: cratering event, impact event, outgassing etc.). The factors which can influence and modify the meteoroid trajectories in the space summarized as follows.

Effects related to the gravitational interactions:

- celestial mechanical perturbations, resonances (mean motion resonances, secular resonances e.g., ν_5, ν_6, ν_{16}), ω or ϖ perihelion precession due to the perturbation. There are other type resonances (e.g., mean motion ones) which can stabilize the orbits for a long time interval.
- chaotic motion (NEAs route to the Sun). Inward motion via resonances: from ν_6, 3/1, 5/2 or from orbits with large e (e.g., Taurid–Encke Complex).
- gravitational focusing (e.g., meteoroids: Earth deflects their orbit to the Moon).
- effects of the internal graviational field of a dense, compact meteoroid swarm.
- collisions which are driven by gravitational motion.

Non–gravitational effects:

- electromagnetic: radiation pressure.
- electromagnetic: motion of the electrically charged dust particles in a magnetic field (e.g., in the solar wind plasma).
- relativistic–electromagnetic: PR (Poynting–Robertson) effect.

- thermal: YORP (Yarkovsky–O'Keefe–Radzievskii–Paddack) effect together with gravitational perturbations: e.g., MB asteroid meteoroid delivery from ν_6 resonance to NEA orbit.
- mechanical: solar wind pressure (for small particles).
- thermal and mechanical: outgassing, sublimation, changing (shrinking) the size of a meteoroid: e.g., ice sublimation, repulsive forces.
- thermal and mechanical: changing the rotational motion parameters (YORP, outgassing effects).

Comets as parent bodies

Comets, cometary nuclei are important objects in the Solar System in that they are primordial: they most closely represent the matter out of which the Solar System was formed. The morphological structure of comet nuclei is described by a fluffy (porous) aggregate of tenth micron silicate core–organic refractory mantle particle on which outer mantles of predominantly H_2O ices contain embedded carbonaceous and polycyclic aromatic hydrocarbon (PAH) type particles of size in the of 1–10 nm range. This characteristics of the dust can be deduced either from comet dust infrared continuum and spectral emission properties or the measurements by the dust dectetors of the in-situ comet spaceprobes (VEGA, GIOTTO). This is demonstrated by comparing results on the comets Halley, Borrelly, Hale–Bopp, and extra–solar comets in the β Pictoris disk. The chemical composition of comet nuclei derived from current data on interstellar dust ingredients and comet dust and coma molecules are shown to be substantially consistent with each other in both refractory and volatile components. When limited by relative cosmic abundances the water in comet nuclei is constrained to be close to 30% by mass and the refractory to volatile ratio is cloes to 1:1. Within the experimental uncertainty the mean abundances of the rock–forming elements in cometary dust particles are comparable to their abundances in carbonaceous CI–chondrites and in the solar photosphere, i.e. they are cosmic. There are databases of meteoroid grains related to the comets collected by stratospheric airplanes (Brownlee's particles). The dust detectors of the in-situ comet spaceprobes VEGA 1 and 2, GIOTTO at the comet Halley analyzed the mass and chemical composition of the dust particles. The results about the rocky material components show that about half of Halley's analyzed particles are characterized by anhydrous Fe–poor Mg–silicates, Fe–sulfides, and rarely Fe metal. The Fe–poor Mg–silicates link Halley's dust to that of Hale–Bopp as shown by recent infrared observations. No significant deviation from normal of the isotopic composition of the elements is unequocially present with the notable exception carbon: ^{12}C-rich grains with $^{12}C/^{13}C$-ratios up to $\approx$5000 link cometary dust to presolar circumstellar grains identified in certain chondrites. The difference between the cometary and typically asteroid related meteoroides can obviously be manifested by the atmospheric entry heating, observed spectra of meteors and physical, chemical characteristics of the falled, collected meteorites.

Let's turn to some intersting point of properties of cometary meteoroid streams. There are meteoroid streams with nodal points very close both to Venus and Earth within 0.1 AU: δ Cancrids, Virginids (1) and (2), Sagittarids, Piscus Austrinids, α Monocerotids, χ Orionids (1) and (2), as well as bolide streams namely α Cancrids and β Librids. Recently it has been already proposed that the α Monocerotids are associated to the comet Van Gent–Peltier–Daimaca 1944

I (C/1943 W1), the χ Orionids could be related to the asteroid–comet transition object 2201 Oljato, and the α Canrids probably can be connected to the asteroid 1993 VD. The comets having perihelion distances inside the Earth's orbit and their nodal points are within 0.1 AU to the orbit of Venus are D/1770 L1 Lexell, D/1917 F1 Mellish, D/1917 D1 Wilk, 5D/Brorsen, 7P/Pons–Winnecke, 12P/Pons-Brooks, 26P/Grigg–Skjellerup, 27P/Crommelin, 35P/Herschel–Rigollet, 72P/Denning–Fujikawa. Some of these associates with known meteorid stream as π Puppids (26P/Grigg–Skjellerup), June Bootids (7P/Pons–Winnecke), and December Monocerotids (D/1917 F1 Mellish) while others are candidates as parent bodies of the meteoroid streams in the inner Solar System.

Very recently in the explanation of the comet related meteoroid outburst the significance of the orbital resonances was enhanced comparing to the initial ejection kinematics of the liberated material from the cometary nucleus. In connection the recent activity of the famous Leonid meteoroid stream it is interesting to highlight about a special cause of the meteor outbursts. This related to the comets in Halley–type orbit as the case of 55P/Tempel–Tuttle. The outburst activity can be described in term of the shape of the spatial distribution of the meteoroid swarm material in the orbit as "filament", "new peak", "ribbon–like" structures, "nodal–blanket" includes a cluster of meteoroids with a small dispersion in radiant and speed. This orbital resonance related phenomena emphasizes a difference between the short–period ($20 < P < 200$ yr) comets and long–period ($P > 200$ yr) comets. The *near–comet type outburst* occures when the parent comet is close to the nodal points of the Earth's orbit while the *far–comet type outburst* takes place when the comet is far from its Earth encountering meteoroid stream. Near–comet type outburst producing comets are 1P/Halley (η Aquarids, Orionids), 55P/Tempel–Tuttle (Leonids) and 109P/Swift–Tuttle (Perseids); far–comet type outburst related comets are Van Gent–Peltier–Daimaca 1944 I (C/1943 W1) (Aurigids), Comet Thatcher 1861 I (C/1861 G1) (April Lyrids), for instance. Halley–type comets and meteoroids tend to librate around a mean–motion resonance (mostly 1:j Jovian resonance): e.g., 1:11 or 1:12. This protects the dust and meteoroids from close encounters with Jupiter. Elsewhere, the particles are dispersed into the annual shower debris stream. Some of this comets are protected from close encounters by Uranus being close to a 2:5 orbital mean–motion resonance. Moreover, the usual higher orbital inclination also protects the meteoroids of Halley–type comets from the perturbations by the major planets. The meteoroids from the long–period comets cannot regulated by the 1:j type mean–motion resonances therefore their remarkable outburst event cannot be formed as in case of the Halley–type comets. Furthermore, a short–period comets associated meteoroid stream is influenced by the stronger perturbations by the major planets due to their proximity and the lower orbital inclination of the stream. So, the planetary orbital resonances may have much more significant influence on the orbital motion of a meteoroid stream than of the initial conditions during the material ejection process from the parent body. However, the initial conditions are obviously important to form the initial orbit of the stream in a shorter time interval just after the ejection. But during the long term evolution of the meteoroid orbits the resonances and other, non-gravitational effects will dominate.

In addition, we are reporting here some information about the nucleus of the 55P/Tempel–Tuttle, the parent body of the Leonids. The high resolution of the excellent optics and detector system of the Hubble Space Telescope (HST) especially applying the Planetary Camera 2 allows to separate the cometary nucleus from the active coma and the supplementary observations with in the thermal infrared domain with the Infrared Space Observatory (ISO) yield the possibility to derive both the surface albedo and size of the nucleus. According to the studies made with the Planetary Camera 2 of the HST and with the ISOCAM imaging detector of the ISO during the last apparition of this comet in 1997/98 the effective radius of this body is about 1.8 km in agreement between the results have been derived by these two instruments. Ground–based observations using the 5-m Hale telescope (SpectroCam–10) determined this effective radius of 2 km. The geometric albedo is low as for other comets, i.e. it is 0.04, and the linear phase coefficient is 0.035 mag/deg. The short time spans of the observations with the HST and ISO do not allow to determine the rotational period of the nucleus but it was concluded that it should be greater than 10 hours. The observations made at Pic–du–Midi suggested two possible values of the rotational period as 15.31±0.3 h or 14.79±0.02 h. The infrared observations of the dust coma were performed with the 5-m Hale telescope and the Infrared Telescope Facility (IRTF) of NASA on Mauna Kea, Hawaii. Both observations agree in absence of the silicate emission or its very weak presence. The infrared spectrum in the 3–14 micron range eventually a Planckian-like which can be explained either by the presence of large dust grains or graphite grains (lack of discrete absorption bands and their emissivity changes slowly with the wavelength). However, most comets usually show silicate emission due to the presence of olivine and/or pyroxene-based particles. The comet 55P/Tempel–Tuttle and some other comets are slightly unique in term of absence of silicate emission, e.g., 23P/Brorsen–Metcalf (23P/1847 O1), 24P/Schaumasse (24P/1911 X1), and C/1998 K5 (LINEAR). Data analysis on the other parameters on the actual activity level exhibited during the last apparition of this comet is in progress now.

Asteroids as parent bodies

Chondrite parent bodies

The primitive nature of chondrites demands that they come from objects that have somehow escaped severe geologic prosessing. This is most readily understood if their parent bodies are small. It is likely that chondrites and chondritic micrometeorites, that is interplanetary dust particles, are derived from the smaller objects in the Solar System, primitive asteroids and comets. C-type asteroids (and their relatives, the G, B, and F-types) and carbonaceous chondrites show similar spectral characteristics. These asteroids have nearly featureless spectra at wavelengths longer than 0.4 μm, but their infrared spectra (near 3 μm) show the presence of hydrated minerals such as phylosilicates. Water bound in to the structures of clay minerals vibrates when it absorbs energy of this wavelength. Minor planet 1 Ceres associates to the CI and CM chondrites and 2 Pallas to the CR condrites. The most probable parent body of ordinary chondrites is the minor planet 6 Hebe (H6-type with IIE-type iron). The asteroid 7 Iris is considered as another ordinary chondritic body with Ca-poor olivine–orthopyroxene meteoritic analogue spectrum. Numerous Near Earth Asteroids show ordinary chondritic spectra (e.g., 1864 Daedalus, 5836 1993 MF are L4, 3352 McAuliffe and 5786 Talos are H6).

Achondrite parent bodies

Collisions among the celestial bodies of the Solar System have provided geologically processed samples of these surfaces and interiors. Altough, for many achondrites we do not know with certainly from which parent bodies are derived, nevertheless, we can make some very informed guesses about the identities of some achondrite parent bodies. Achondrites as the HED (Howardite–Eucrite–Diogenite) types for example yield information both on the interior stratigraphic layers of the parent body itself and on the impact process which removed the meteoroid material from the parent body. Eucrites are basaltic flows, and diogenites are plutonic (magmatic–like) rocks that formed at deeper interior levels. Howardites are mixtures of eucrite and diogenite excavated in impact events. The minor planet 4 Vesta (*vestoid*) is the prototype of the parent bodies of the HED-type meteoroids (”chips” of Vesta) . The E-type asteroids 44 Nysa and 3103 Eger, M-type asteroid 135 Hertha, Moon related achondrites and Mars originated SNC meteorites belongs to this meteorite group. 44 Nysa and 135 Hertha is known as the fragments of a larger minor planet: Hertha is its core and Nysa its silicate mantle (aubrite parent body).

Iron and stony–iron parent bodies

These are samples of the metallic remnants that once must have undergrided the rocky parts of differentiated asteroids. Their parent bodies, if they still exists, are denuded cores from which the overlying silicate mantles and crusts have been stripped off and reduced to rubble. Spectra of metallic as M-type asteroids show that they are characterized by sloping spectra that resemble those of iron meteorites (e.g., 16 Psyche). In contrast, A-type asteroids exhibit a prominent absorption band at $1\,\mu$m, characteristic of olivine. Asteroids like 246 Asporina are likely candidates for pallasite parent bodies. The distribution of various spectral classes of asteroids indicates that plausible parent bodies of irons (M asteroids) and stony–irons (A and possubly some S asteroids) are located in the inner asteroid belt, mostly between 2 and 3 AU. The A asteroids are too rare to be shown as a percentage of the total asteroid population, but the approximate orbital distances of them are between 2.5 and 3.5 AU: 246 Asporina, 289 Nenetta, 446 Aeternitas, and 863 Benkoela, for example. Recently an unanswered question remained whether all the bodies in the inner asteroid belt had been partially melted and differentiated. The presumed T Tauri phase of our Sun in its early evolutionary history can explain some material transformation due to the surface heating in the inner asteroid belt. The internal differentiation of the small bodies can be explained either by that they are inner core of larger bodies or slow radiogenic heating (*onion* shell structured, layered body), as well as if they are large enough some differentiation can take place.

Future work, suggestions

There are some interesting question to be studied in mode detail by the amateur meteor observers in the near future. Here are these summarized briefly as follows:

- Improving of determination of the orbits of meteors or meteoroids via corresponding multi–site observations of the same meteor simultaneously (applying the method of triangulation, for instance). These observations can be made from domestic observational sites with relatively short base–lines (on ∼10 or 100 kilometers). There were some good example for this type of cooperations observing bolides, for instance. In the frame of organized campaigns this would be a useful task. It would be nice to find the meteorite body according to the trajectory determination, moreover, to determine the orbit of the meteoroid in the Solar System.

- Observing special meteor outburst events: as the effects of the Solar reflex motion and the orbital perturbations of the meteoroid stream by the major planets (e.g. by Jupiter, Saturn and Earth). For this an excellent example was the outburst of Aurigids in 1986. Other outburst are also interesting as Θ Aurigids, Lyrids and Quadrantids.

- There are some meteoroid streams which are very interesting and puzzling: e.g. Lyrids in April.

- It is extremely important to solve the puzzle of the various meteoroid streams in June. These prominent meteoroid streams could be responsible for some terrestrial and lunar surface impact event (observed in Canterbury, England in 1178 and Tunguz phenomena in 1908; as well as they can explain some seismic event on the Moon's surface detected by the seismic stations left by the Apollo missions). However, still there are questions about the characteristics of the meteoroid streams being suspected for the meteor or impact events could be occured in June. These streams in June to be observed are the β Taurids and Corvids.

- It is a new perspective to make video and CCD monitoring of the Moon surface especially its dark side in June in order to detect some possible meteoroid impact events as it has been already done during the Leonids in 1999. Continuing the "quasi–TLP" (Transient Lunar Phenomena) observing program but recently applying modern detectors these "Lunar flashes" can be observed by small telescopes (e.g. with objective diameters of 15–25 cm).

- To perform carefully prepared observing campaign for the Leonids including the video, CCD monitoring of the Moon surface during the activity interval of the stream.

- Since there are meteoroid streams intercepting the orbit of Venus it would be very interesting to monitor the night side of this planet to detect possible atmospheric event of larger meteoroids in the frame of "International Venus Watch" to observer "Venus flashes". The technics is applied is similar as in case of the Lunar surface monitoring.

- Constructing and applying all–sky cameras with modern computerized imaging technics would be useful.

- It is worth-while to enlarge the observing activity toward the radio frequencies both with passive and active radio observing methods. Some interesting streams are as Lyrids, Perseids, June Bootids etc.

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