Active small bodies in the Solar System over a wide range of heliocentric distances

5 – 8 SEPTEMBER 2023

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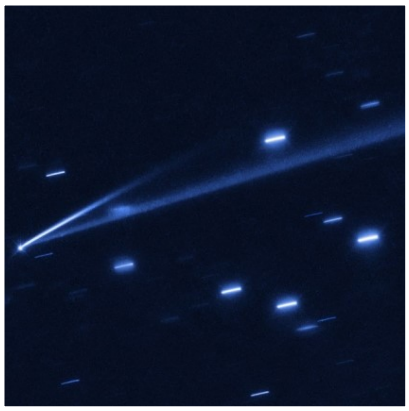

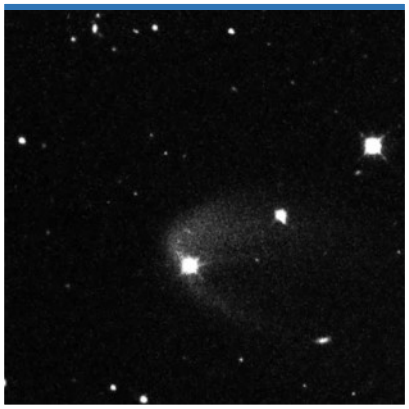

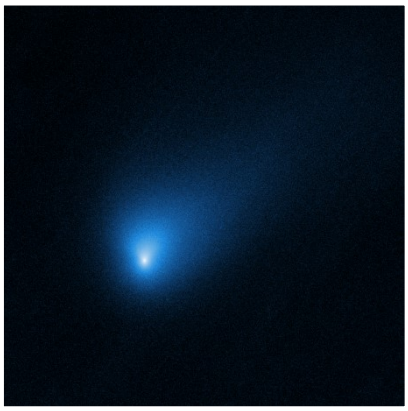

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Welcome

The workshop provides a cross-disciplinary knowledge exchange on the physics of the small bodies in the Solar system revealing a comet-like activity, new space missions (Comet Interceptor, DESTINY+, Lucy, DART), and related ground-based observational campaigns.

The workshop is organized by the Astronomical Institute of Slovak Academy of Sciences in Tatranská Lomnica.

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ACTIVE SMALL BODIES IN THE SOLAR SYSTEM
OVER A WIDE RANGE OF HELIOCENTRIC
DISTANCES

5-8 September 2023, Stará Lesná,
Slovakia

PROGRAM

Monday 4th September	
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9:30	**Stavro Ivanovski** (key note talk) *Cometary coma models*
10:00	**Dennis Bodewits** *Probing Radiative Processes in Cometary Atmospheres: Spectral Modeling, Observational Opportunities, and Challenges*
10:15	**Juraj Országh** *Excitation-Emission Cross Sections for Electron Impact Excitation of Carbon Monoxide*
10:30 – 11:00	**COFFEE BREAK AND POSTER SESSION**
11:00	**Michael Kelley** (key note talk) *JWST observations of two short-period comets*
11:30	**Jean-Baptiste Vincent** (key note talk) *Morphological evolution of cometary surfaces*
12:00	**Cyrielle Opitom** *Using IFUs to characterize the distant activity of comets*
12:15	**Bryce Bolin** *The volatile content of giant Oort cloud comet C/2014 UN271 during its return to the planetary region*
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14:30	**Noria Brecher** *Structural changes of illuminated water ice samples*
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16:15	**Said Hmiddouch** *Monitoring the activity and the composition of comet C/2017 K2 (PANSTARRS)*
16:30	**Mikołaj Sabat** *New Constraints on Cometary Activity of 'Oumuamua from Lyman-alpha Images Obtained by SOHO/SWAN*
16:45	**Simon Anghel** *Meteoroid mass estimation based on well-known atmospheric impacts*
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9:30	**Carey Lisse** *Consequences for Solar System Formation and Evolution of the Early Activity & Removal of Bulk Hypervolatile CO, N_2, and CH_4 Ices by Evaporative Sublimation from Small Bodies*
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10:15	**Silvia Ďurišová** *Dealing with the parent bodies in the Meteor Data Center*
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11:45	**Joel Parker** *Close Observations of Outer Solar System Small Bodies*
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Gabriel Borderes Motta *May a comet dynamically capture and keep meteoroids in its vicinity?*
Mária Hajduková *No evidence for interstellar meteors in the CNEOS database*
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List of talks

Tuesday 5th

Chemical composition of comets

Biver, N.[1*]
[1]LESIA, Observatoire de Paris – PSL, CNRS, Sorbonne Univ., Univ. Paris-Cité, France, (nicolas.biver@obspm.fr)

The composition of cometary nuclei has been investigated by remote sensing of its coma from UV to radio wavelengths for decades, revealing about 30 cometary molecules [1]. In-situ investigation and monitoring of comet 67P/Churyumov-Gerasimenko by the Rosetta mission has more than doubled the number of identified cometary molecules in the coma and brought us more information on the sublimation behavior of the various species. A large diversity of molecules has been observed, from very volatiles driving the activity of the comets to semi-refractories like ammonium salts. Some of these molecules show evidence that they are mostly produced in the coma and not parent species sublimating directly from the nucleus. On the other hand, a large compositional diversity is present in the comet sample observed remotely. Molecular relative abundances can vary by one order of magnitude if not more among comets as well as with heliocentric distance for a given comet. Isotopic ratios, especially the D/H in water also varies between comets. While the organic content of the comet seems to have inherited from the proto-solar cloud, diversity likely traces the various conditions present in the proto-planetary when and where cometary ices condensed.

References

[1] Biver, N., Dello Russo, N., Opitom, C., Rubin, M. Chemistry of comet atmospheres. *In Comets III*, eds. K. Meech and M. Combi, Univ. of Arizona Press, 2023, in press. `https://doi.org/10.48550/arXiv.2207.04800`.

NOTES

Cometary (Dust) Coma Models

Ivanovski, S.L.[1,2]
[1]INAF – Astronomical Observatory of Trieste, Italy (stavro.ivanovski@inaf.it), [2]University of Trieste, Italy

Cometary science has been brought to a new level with the Rosetta findings. Timely, multi-instruments data analyses are now progressing a step forward in understanding how comet works and are providing critical results for a more comprehensive and unified knowledge of cometary dust environments. I will summarise the recent advancements on cometary coma models reviewing several main aspects: the development of multidimensional cometary gas and dust models, linking gas and dust models, dust models diversity and approaches and how advanced models together with the enriched cometary data can revision our understanding of comet formation and lead to reconsider established concepts related to the formation and evolution of the Solar System. In addition, I will discuss the need of both a complex model, that sufficiently enough addresses the "synergy" in the exploitation of cometary data sets, and "simple" models that can reasonably good reveal the cometary physical properties for forthcoming cometary missions as Comet Interceptor. Finally, I will note how scaling laws and AI techniques can be used with cometary model data to investigate cometary coma dust structures and cometary surface.

NOTES

Probing Radiative Processes in Cometary Atmospheres: Spectral Modeling, Observational Opportunities, and Challenges

Bodewits, D.[1*], Bonev, B.P.[2], Cordiner, M.A.[3], and Villanueva, G.L.[3]
[1]Auburn University, Auburn, AL 36830, USA, [2]American University, Washington DC, 20016, USA, [3]NASA GSFC, Greenbelt, MD 20771, USA

Cometary atmospheres offer unique natural laboratories for studying radiative processes spanning a wide range of wavelengths, from radio to X-rays. These radiative processes offer a wealth of information about the early solar system, astrophysics, astrochemistry, and planetary science [1]. In this contribution, I will review the current understanding of radiative processes in cometary atmospheres, focusing on spectral modeling, observational opportunities, and anticipated challenges in the interpretation of new observations.

Observations of cometary emissions provide measurements that serve as diagnostics for various properties of the nucleus and the coma. These measurements include column densities, production rates, relative abundances, rotational and kinetic temperatures, photodissociation scale lengths and lifetimes, gas outflow velocities, plasma structures, and the rotational state of the nucleus, among others. The interpretation of these metrics in terms of chemical composition, isotopic abundances, and physical and chemical evolution of volatiles in small bodies is crucial for understanding the early solar system. Furthermore, comets act as natural laboratories for studying a variety of chemical and physical phenomena, including ice sublimation, volatile release and acceleration, thermal processing of grains, photochemistry, and ionospheric processes.

Advancements in observational facilities, such as the James Webb Space Telescope and large ground-based telescopes, will usher in a new era of cometary exploration, enabling the study of fainter and more distant cometary targets. A recent example includes the detection of water around 238P/Read at 2.4 au at a production level as low as 0.30 kg/s [2]. These new observations will contribute to the comprehensive understanding of cometary processes and their variability over the comet's orbit. Spectro-spatial observations across different wavelengths will provide insights into the macroscopic and microscopic motions, compositions, and physical conditions of cometary gases. Additionally, increased spectral resolution and improved sensitivity will allow for the detection and characterization of new atomic and molecular species, providing valuable data for understanding cometary composition and processes.

To fully exploit the observational capabilities, accurate theoretical and laboratory data are required. Collisional excitation and de-excitation rate coefficients, photodissociation lifetimes, and comprehensive spectroscopic line lists need further development to enhance the reliability of physical models and improve the interpretation of observational data.

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[2] Kelley, M. S. P., Hsieh, H.H., Bodewits, D., Saki, M., Villanueva, G.L., Milam, S.N., and Hammel, H.B., Spectroscopic identification of water emission from a main-belt comet, *Nature*, 2023, in press.

NOTES

Excitation-Emission Cross Sections for Electron Impact Excitation of Carbon Monoxide

Országh, J.[1*], Stachová, B.[1], Blaško, J.[1], Bodewits, D.[2], Bromley, S.[2], Matejčík, Š.[1]
[1]Dept. of Experimental Physics, Comenius University in Bratislava, Slovakia,
(juraj.orszagh@uniba.sk), [2]Physics Dept. Auburn University, Alabama, USA

Electron induced collisions play an important role in atmospheres of planets or cometary comas. The slow secondary electrons created mostly by photoionization collide with neutral gas molecules and induce various kinds of excitation reactions. In specific conditions the subsequent light emission can be surprisingly strong [1]. The local conditions such as pressure, temperature or other reactions with present species significantly affect the emission of the object. To fully analyze astronomical observations of these processes the database of emission spectra taken at well-defined laboratory conditions is helpful and models including the emission inducing reactions are necessary.

We report the laboratory emission spectra induced by monochromatized electron impact on carbon monoxide. The spectra were taken at various energies in the interval $5-100$ eV (see figure) and provide a complete emission map for $300-1050$ nm spectral range. The reaction thresholds, emission cross-sections and their dependence on collision energy can be easily derived from the map for all the detected transitions within the limits of optical resolution of the experimental system.

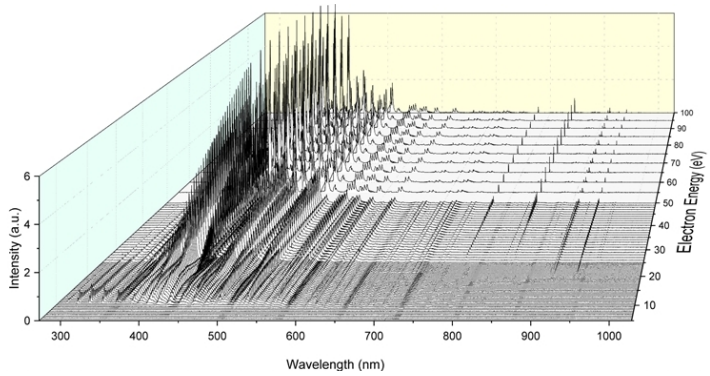

Figure 1: Electron induced emission map of carbon monoxide.

Acknowledgments
This work has received support from Slovak Research and Development Agency under the projects nr. APVV-19-0386 and APVV-15-0580, Slovak grant agency under projects nr. 1/0489/21 and 1/0553/22. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871149.

References
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NOTES

JWST observations of two short-period comets

Kelley, M.S.P.[1*]
[1]University of Maryland, College Park, USA, (msk@astro.umd.edu)

JWST is an infrared optimized 6.5-m space telescope located at the Earth-Sun L2 point. With spectral sensitivity from 0.6 to 28 μm, its instrumentation is well-matched to observe many aspects of active objects, including scattered sunlight and thermal emission from dust, and gas fluorescence band emission from several key molecules. In this presentation, we discuss JWST observations of two short-period comets: 22P/Kopff and 238P/Read. Both comets were observed with the NIRSpec instrument using the integral field unit, providing spatially resolved spectra over a $3'' \times 3''$ field of view, with $0.1'' \times 0.1''$ spatial sampling. The spectrum of Jupiter-family comet 22P/Kopff shows typical cometary emission features, such as water at 2.7 μm, several organic molecules at 3.4 μm, and carbon dioxide at 4.3 μm [1]. We show these data and discuss their derived abundances and spatial distributions. In contrast, the spectrum of main-belt comet 238P/Read only shows the 2.7 μm water band, and the derived upper limit to the CO_2-to-H_2O ratio is about an order of magnitude lower than any other telescopically observed comet at a similar heliocentric distance [2]. The detection of water at 238P/Read is the first observation of any volatile in a main-belt comet, a class of objects that have orbits within the asteroid belt, but show the behaviors of comets (comae and tails). The lack of CO_2 in the coma of comet Read is consistent with a long residence time in the asteroid belt and adds evidence to the idea that the outer belt has a large reservoir of ancient water ice.

References

[1] Kelley, M. S. P., Protopapa, S., Wong, I., et al. JWST observations of comet 22P/Kopff, in preparation.
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NOTES

Morphological evolution of cometary surfaces

Vincent, J.-B.[1*]
[1]DLR Institute of Planetary Research, Berlin, Germany (jean-baptiste.vincent@dlr.de)

Cometary activity, i. e. the release of gas and dust from a comet nucleus has been observed at many scales, and for many objects. The process is generally understood as arising from the sublimation of volatile species, and subsequent ejection of refractory material. It leads to the formation of an anisotropic dust and gas coma around the nucleus, modulated by the topography and local distribution of ices. Over the last decade, many authors have improved the description and interpretation of cometary activity, and developed complex models that attempt to describe the flows of gas and dust expanding away from the comet surface [1, 2].

Among the many open questions about cometary activity, we will focus this presentation of the specific aspect of understanding what activity actually does to the surface. All comets visited so far, with the exception of 1P/Halley, are Jupiter Family Comets that experienced multiple orbits at heliocentric distances where ices in the first surface layers can sublimate and trigger transformations of the terrain. Every nucleus observed by a space mission displays morphological features that are indicative of some form of regressive erosion (cliff collapse, expansion of local depressions,...) but it is challenging to establish a direct link between energy input, surface properties, and surface changes. In particular, the timescale of changes is difficult to estimate, mostly due to the lack of available data. In fact, we have observed changes on only two comets [3, 4]: 9P/Tempel 1 after one orbit (NASA's Deep Impact and Stardust/NEXT missions), and 67P/Churyumov-Gerasimenko during one perihelion passage (ESA's Rosetta mission). Another important process discovered by Rosetta is that not all activity leads to erosion. A significant amount of refractory material does not escape the nucleus and is instead deposited elsewhere, leading to a local ponding of material [5].

These processes, and their interrelation, challenge our understanding of what is a pristine cometary surface. E. g. what does a comet look like, shortly after being formed? This question is going to be addressed by ESA's Comet Interceptor [6], but we can already develop our understanding of cometary evolution using existing data. I will review some of the most recent results from multiple teams that worked on the characterization of surface changes on comet 67P [6, 7, 8], and a from a recent citizen science project [9].

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NOTES

Using IFUs to characterize the distant activity of comets

Opitom C.[1]
[1]University of Edinburgh, United Kingdom, (copi@roe.ac.uk)

The last decade has seen the advent of large field of view Integral Field Spectrographs (IFUs) for observations at optical wavelengths. These instruments, such as MUSE on the 8-m Very Large Telescope [1], present an interesting opportunity to characterize the distant activity of comets, due to the combination of spatial and spectral information they provide.

In the case of distant comets, for example, it has been shown that the combination of large field of view, spatial, and spectral information provided by IFUs can be used to retrieve the flux of three forbidden oxygen lines [OI] at 557.7339, 630.0304, and 636.3776 nm, even for faint objects [2,3]. Since the excited oxygen atoms responsible for these lines are produced in the coma of comets by the dissociation of oxygen-bearing species (mainly H_2O, CO, and CO_2), forbidden oxygen lines, and in particular their ratio, can be used to probe the drivers of cometary activity at different distances from the Sun [4]. Observations of the 630 nm [OI] line with the MUSE IFU have already provided the lowest ground-based measurement of the water production rate for comet 67P in parallel to the Rosetta mission [3]. A recent study also indicates that the ratio between the green (557 nm) and the two red line (630 and 637 nm), usually referred to as G/R ratio, can be derived using MUSE observations. The G/R ratio has been used to estimate the H_2O/CO_2 ratio in the coma of comets [5]. [6,7] have also shown that the high G/R ratio measured for comets C/2016 R2 and 2I/Borisov was due to unusually high CO abundances and might be used to identify comets with very high CO abundances.

IFUs are generally very sensitive to faint extended emission and are thus ideal tools for the observations of active small bodies in the solar system. This talk will explore how IFUs can contribute to our understanding of the distant activity of small bodies by mapping forbidden oxygen lines and how future IFUs on even larger telescopes will likely push this opportunity even further.

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NOTES

The volatile content of giant Oort cloud comet C/2014 UN271 during its return to the planetary region

Bolin, B.T.[1], Brown, M.E.[2], Saki, M.[3], Bodewits, D.[3], Chen, C.H.[4], Fernández, Y.R.[5], Lisse, C.M.[6], Morbidelli, A.[7], Noll, K.S.[1], Protopapa, S.[8]

[1]Goddard Space Flight Center, Greenbelt, MD 20771, USA, [2]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA, [3]Department of Physics, Edmund C. Leach Science Center, Auburn University, Auburn, AL 36849, USA, [4]Space Telescope Science Institute, Baltimore, MD 21218, [5]Department of Physics & Florida Space Institute, University of Central Florida, Orlando FL 32816, USA, [6]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA, [7]Laboratoire Lagrange, CNRS, Observatoire de la Côte d'Azur, Nice, 06300, France, [8]Southwest Research Institute, Boulder, CO 80302

Comets are relatively-pristine remnants of the original planetesimals that were ejected from the planetary region in the late stages of planetary formation. The Oort cloud comet C/2014 UN271, hereafter UN271, is $\sim$140 km in diameter [1,2,3], large enough that it could be an intact example of a planetesimal that formed in the protoplanetary disk before being ejected into the Oort cloud [4]. UN271 is currently beyond 17 au from the Sun as it moves to a perihelion distance of 11 au in 2031. Given its large heliocentric distance the temperatures on and below its surface are too low for efficient sublimation of water ice. It is likely that its activity is driven by hypervolatiles such as CO or CO_2 and not H_2O [1,5]. It is dynamically new on its first inbound trip to the Solar System's planetary region [6] providing the rare opportunity to study the volatile content of one of the original planetesimals in a pristine state.

We present JWST/NIRSpec prism IFU [7] observations of UN271 with $R\sim100$ covering the spectral range where we can detect emission features from the vibrational bands of the gas-phase all the main volatiles found in comets (such as CO_2, CO and C_2H_6). Moreover, this range also includes absorption bands of solid-phase water-ice grains [8,9]. Our observations, taken on December 22, 2022, when the comet was at 18.6 au from the Sun, provides constraints on the comet's CO and CO_2 production rates, the activity driving mechanism [5], the presence and nature of water-ice grains in its coma and can be compared with similar spectra of Kuiper Belt bodies [10].

We will discuss the implications for the timing of the formation of the original planetesimals [e. g., 11] as well as UN271's formation environment within the primordial Kuiper Belt.

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NOTES

Comet Simulation in the Laboratory

Kreuzig, C.[1*], Blum, J.[1]
[1]TU Braunschweig, IGEP, (c.kreuzig@tu-braunschweig.de)

In this work I will present the laboratory experiments we designed and built in the CoPhyLab project for the simulation of comets. Since the comet as a system is very complex we decided to build some small experiments to study individual parameters, for example heat conductivity, particle ejection or tensile strength. This experiments are mostly performed with single component samples like water ice or dust, but mixtures are also possible. In addition to the small experiments one large L-Chamber was constructed, which combines a total of 14 instruments and can provide cometary like environments for several weeks. The samples can weigh several kilograms and have a diameter of 25 cm. The whole chamber is described in detail in Kreuzig et al. [1].

For the experiments, specially the large L-Chamber samples, a new water ice production method was designed, which will also be presented.

Lastly, I will show the typical results from the experiments performed and explain the technical difficulties, but also new opportunist our laboratory setup provides.

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NOTES

Structural changes of illuminated water ice samples

Brecher, J.N.[1*], Kreuzig, C.[1], Blum, J.[1]
[1]TU Braunschweig IGEP, Germany, (j.brecher@tu-braunschweig.de)

In the CoPhyLab at the TU Braunschweig, the goal is to simulate the physical behavior and properties of comets in the laboratory. Therefore, we are currently investigating the behavior of illuminated granular water ice samples in one of our thermal vacuum chambers. We are also studying samples composed of different mixtures of silicate dust and water ice.

We perform experiments on activity, opacity as well as on surface and structural changes with different illumination intensities. We also investigate the influence of structures in the sample. Throughout our experiments housekeeping data such as pressure and temperature are collected and a high-speed camera as well as a high-resolution camera are used. The used granular water ice is made with our homemade water ice machine and has a particle size of $2.5\,\mu$m.

During this conference we will present some of our results on the behavior and changes of illuminated granular water ice samples.

NOTES

Following the superficial water ice content in sublimating ice-dust mixtures

Feller, C.[1,2*], Pommerol, A.[2], Kieffer, K.[2]
[1]LESIA, Observatoire de Paris, PSL Research University, CNRS, Univ. Paris Diderot, Sorbonne Paris Cité, UPMC Univ., Paris VI, Sorbonne Université, 5 Place J. Janssen, Meudon Cedex 92195, France, [2]Physikalisches Institut, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

Introduction: As the ESA/Rosetta mission brought forward numerous observations and results regarding the cometary nucleus, the inner and outer comas, unraveling the mechanisms driving cometary (and cometary-like) activity stands as a momentous as well as present field of investigations (Kaufmann+2018, Groussin+2019, Kossacki+2022, Lethuillier+2022). In particular, the monitoring of a sublimating surface's relative composition in a laboratory setting stands as a stepping stone for the subsequent analyses and modelling of the surface properties (e. g. geomorphological changes and thermal wave modeling). We report here the results of a retrieval method to determine the superficial water ice content from the surface reflectance in the context of a sublimation experiment with an intimate ice-dust mixture.

Methods: We have selected three well characterized samples for our experiments: spherical water-ice particles prepared through a process internal referred to as "SPIPA-B" (Pommerol+2019), and two asteroids simulants distributed by the University of Central Florida (Britt+2019). We performed several physical measurements to determine additional properties of the considered asteroids simulant (e. g.: grain densities, porosity, and particle-size distribution). We measured the visible reflectance phase-curves of the end-members and intimate mixtures using the PHIRE-2 goniometer. Two of these mixtures were left to sublimate for tens of hours with variable illumination at a pressure below 2×10^{-5} mbars and a temperature below 180 K. Their surface was regularly monitored with the MoHIS spectro-imager observing the surface across the visible and the near-infrared domains (from 400 nm to 2450 nm).

Results: From the measured phase-curves, we obtained photometric model parameters for the "Hapke reflectance model" (Hapke+1993). Combining the known and measured physical properties with the photometric model parameters, we inverted spectral mixing formulas to estimate the superficial water-ice content of the mixtures and their evolution with time. We presented the results of experiments with water ice/volatile-rich asteroid simulant (CI-type) intimate mixtures in Feller+2019. We will present here the experimental results with the water ice/volatile-depleted asteroid simulant (CR-type) intimate mixture and discuss the implications of our result in the context of the CoPhyLab international project (Lethuillier+2022), cometary missions and our general understanding of cometary activity.

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NOTES

Stationary expansion of gas mixture from a spherical source into vacuum

Zakharov, V.V.[1*], Rotundi, A.[2,3], Bockelée-Morvan, D.[1], Bykov, N.Y.[4], Fulle, M.[5], Biver, N.[1], Della Corte, V.[2,3], Rodionov, A.V.[6], and Ivanovski, S.L.[5]

[1]LESIA, Observatoire de Paris, France, (vladimir.zakharov@obspm.fr), [2]INAF Istituto di Astrofisica e Planetologia Spaziali, Italy, [3]Università degli Studi di Napoli Parthenope, Italy, [4] Peter the Great St. Petersburg Polytechnic University, Russia, [5]INAF – Osservatorio Astronomico, Italy, [6]Russian Federal Nuclear Center, All-Russian Research Institute of Experimental Physics (RFNC-VNIIEF), Russia

The nucleus of a comet is composed of a mixture of diverse ices and refractory materials. The ices heated by the solar illumination are sublimated and form the gas coma. Depending on the heliocentric distance of the nucleus during its motion along the trajectory, the gas flow in the coma can vary from free-molecular to fluid.

Many approximations (simplified models) of the gas coma require the link of the nucleus surface parameters (gas production and temperature) with (1) parameters of gas flow beyond the acceleration region, and/or (2) parameters of the gas flux back-scattered towards the surface. In addition, coma models based on the fluid description of the gas flow require the relation of the nucleus surface parameters with gas flow parameters on the top of the Knudsen layer (unavoidably existing in the vicinity of the surface).

In the present study we consider a stationary flow of pure gas (H_2O, CO_2, CO) as well as of gas mixtures from a spherical surface. It is assumed that gas production of the surface is a consequence of sublimation within the surface layer. The detailed study of the structure and parameters of the gas out flow is based on the kinetic approach and performed with the Direct Simulation Monte Carlo (DSMC) method. The study covers flow conditions from fluid to free molecular $(K_n = 10^{-5} - 10)$. The results of the study allow us to relate the production rate and temperature of the surface with: (1) back fluxes of mass, momentum and energy toward the surface from the gas environment; (2) parameters of the gas flow on the top of the Knudsen layer; (3) velocities and abundances of gas species beyond the acceleration region. Also, we define regions and conditions where the fluid approximation of the flow can be correctly applied.

NOTES

The effect of early history on the activity of comets – long-term evolution models

Prialnik, D.[1]
[1]Tel Aviv University, Israel, (dinak@tauex.tau.ac.il)

Comets are presumed to have formed and evolved at large heliocentric distances (> 20 au), where the ambient temperatures are sufficiently low for preserving volatile ices, if not at the surface, then perhaps in the interior. We present results of numerical simulations of the long-term evolution of small bodies, composed of amorphous water ice, dust grains and ices of other volatile species that are commonly observed in comets: CO, CH_4, C_2H_6, CO_2, NH_3, HCN, etc. [1]. The heat sources are solar radiation and decay of short-lived radionuclides ^{26}Al and ^{60}Fe. The bodies are highly porous and gases released in the interior flow to the surface through the porous medium. The aim is to find which ices are retained and at what depths.

For example, assuming a circular orbit at distance of $\sim$40 au, a uniform surface temperature, and a density of 0.5 g/cm – the most volatile ices, CO and CH_4 , are found to be depleted even at the center of the body over a time scale on the order of 100 Myr. Sublimation fronts advance from the surface inward, and when the temperature in the inner part rises sufficiently, bulk sublimation throughout the interior reduces gradually the volatile ices content until these ices are completely lost. However, all the other ices survive. At 100 au, CO is depleted, but CH_4 survives to present time, except for a few meters thick outer layer. At a distance of 200 au, even CO survives at a depth of 10 m.

Since CO is abundantly detected in cometary comae, the conclusion of this study is that the source of highly volatile species in active comets is gas trapped in amorphous ice. In fact, the primordial presence of hypervolatile ices in comet progenitors protects the amorphous ice and the volatiles trapped in it, by keeping the temperature far below the crystallization range.

Loss of volatile ices and crystallization of amorphous ice may also occur during the migration phase between the formation site of comets and their present location. As an example, the evolution during the transition between the Kuiper belt region and the Centaur region is followed for a body with the characteristics of 29P/Schwassmann-Wachmann 1, which is a highly active object orbiting at the inner edge of the Centaur zone [2]. It is shown that the present activity may be driven by crystallization of amorphous ice and release of trapped gas (CO), if the transition period does not exceed a few tens of Myr.

By contrast, during the early evolution of Main Belt Comets, assuming they formed in place, all ices except for water ice are lost, and the H_2O ice crystallizes, if initially amorphous. The water ice, too, is depleted down to large depths, so that any present activity should be driven by newly exposed water ice [3], e. g., by impacts. Other volatiles, if present, should have been trapped as clatharate hydrates, either at formation or during crystallization.

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NOTES

On temporal variations of linear polarization in several recent comets

Zubko, E.[1*], Chornaya, E.[2], Zheltobryukhov, M.[2], Kochergin, A.[2], and Videen, G.[3]
[1]Institute for Basic Science, Republic of Korea, (evgenij.s.zubko@gmail.com), [2]Institute of Applied Astronomy of Russian Academy of Science, Russia, [3]Space Science Institute, USA

The degree of linear polarization is a light-scattering characteristic widely known for its high sensitivity to microphysical properties of scatterers. It was studied in various comets (e. g., [1]). It was found that all the comets reveal the phenomenon of negative polarization at small phase angles $\alpha < 30^\circ$ and the positive polarization at larger phase angles. Interestingly, comets reveal a significant dispersion of maximum value of their positive polarization $P_{\max}$, spanning the range from $\sim$5% to $\sim$35%. Based on the amplitude of the positive polarization, comets were categorized into the low-$P_{\max}$ comets and high-$P_{\max}$ comets (e. g., [1]). However, the vast majority of these observations were performed on a very limited number of epochs and, hence, temporal stability of the polarimetric response is poorly known.

At the Ussuriysk Astrophysical Observatory, a division of the Institute of Applied Astronomy of Russian Academy of Science (code C15), we are conducting an observational campaign aimed at monitoring the polarization of comets. Since 2018, we have investigated a number of them, including 21P/Giacobini-Zinner [2], 29P/Schwassmann-Wachmann [4], 46P/Wirtanen [6], C/2017 K2 (PanSTARRS) [5], C/2018 V1 (Machholz-Fujikawa-Iwamoto) [7], C/2019 Y4 (ATLAS) [8], and C/2020 S3 (Erasmus) [3]. In more than half of these objects, we have found noticeable temporal variations occurring within only a few days. It is worth noting that Comet C/2020 S3 (Erasmus) even changed its class within the $P_{\max}$ classification. Although variations of polarization in Comets 21P/Giacobini-Zinner and 46P/Wirtanen were unambiguously detectable, their amplitude was not very large. A truly outstanding increase of positive polarization was detected in Comet C/2019 Y4 (ATLAS) upon its disintegration. Nevertheless, polarization of this comet was not stable even prior to disintegration. However, polarization in the other three comets has not revealed temporal variations.

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NOTES

Monitoring the activity and the composition of comet C/2017 K2 (PANSTARRS)

Hmiddouch, S.[1,2*], Jehin, E.[1], Vander Donckt, M.[1], Jabiri, A.[2], Moulane, Y.[3], Manfroid, J.[1], and Benkhaldoun, Z.[2]

[1]Space sciences, Technologies & Astrophysics Research (STAR) Institute, University of Liège, Belgium, (shmiddouch@uliege.be), [2]Oukaimeden Observatory, High Energy Physics and Astrophysics Laboratory, Cadi Ayyad University, Marrakech, Morocco, [3]Physics Department, Leach Science Center, Auburn University, AL 36832, USA

Introduction: Comets are remnants of the early Solar System, as they formed from icy and dusty material 4.6 billion years ago. Therefore, their study provides valuable information on the physicochemical environment of the early Solar System. The dynamical distribution of comets has evolved since then, most notably due to the migration of giant planets. Today, the main reservoirs are the Oort cloud, source of the isotropic Oort cloud comets or long-period comets with orbital periods exceeding 200 years, and the Kuiper Belt, source of the Jupiter Family Comets. We report on the results of a long photometric monitoring of comet C/2017 K2 (PanSTARRS), hereafter 17K2, with the TRAPPIST telescopes [1]. 17K2 is an Oort cloud comet discovered by the PanSTARRS survey in 2017 [2], at a large heliocentric distance of 16 au. The comet was later identified in archival imagery to be active at 23.8 au from the Sun, the second most distant discovery of an active comet [3], this suggests that the comet's activity is likely driven by CO and CO_2 ices, which are among the most abundant species afterwater. Notably, CO was detected in 17K2's coma within the sub-mm range when it was at a heliocentric distance of 6.7 au, leading to the conclusion that 17K2 is a comet rich in CO [4]. The detection of comets at such extensive distances is becoming more frequent; however, it remains a rare occurrence to investigate a well-preserved comet surface originating directly from the Oort Cloud or following a several-million-year orbit, particularly if it belongs to an uncommon category.

TRAPPIST observations: 17K2 reached its perihelion on 2022 December 19 ($r_h = 1.8$ au, $\Delta = 2.5$ au) and became a bright target, offering favorable observing conditions, particularly in the Southern hemisphere. We started observing 17K2 with TRAPPIST-North on October 25, 2017, using broad-band filters when the comet was still at 15 au from the Sun with a magnitude of 18. We started collecting broad and narrow-band images with TRAPPIST-South on September 9, 2021 ($r_h = 5.4$ au) when the comet became visible and bright from the southern hemisphere. We monitored the activity of 17K2 on both sides of the perihelion until now. We detected close to perihelion emission of NH, OH, CN, C_2, and C_3 radicals as well as the dust continuum in four bands. By fitting the observed gas profiles with a Haser model and after subtraction of the dust continuum, we derived the gas production rates. From the continuum and broad-band images, we computed the $Af\rho$ parameter, a dust production proxy. In this work, we present the magnitude evolution of 17K2 over the last 5 years (2017–2023), as well as the gas and dust activity for several months as a function of time and heliocentric distance.

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NOTES

New Constraints on Cometary Activity of ’Oumuamua from Lyman-alpha Images Obtained by SOHO/SWAN

Sabat, M.[1*], Drahus, M.[1]
[1]Jagiellonian University in Kraków, Poland, (msabat@oa.uj.edu.pl)

’Oumuamua is the first confirmed interstellar minor body observed in the Solar System. The object was discovered by the Pan-STARRS survey on 19 October 2017, when it was located 1.2 au from the Sun and 0.2 au from the Earth. Ultra-deep imaging of ’Oumuamua by the largest telescopes showed no signs of comet-like coma or tail, providing strong evidence that the object is an asteroid (Meech et al. 2017, *Nature* 552, 378; Drahus et al. 2018, *Nat. Astron.* 2, 407) Also spectroscopic investigations did not reveal any traces of gas emissions (Ye et al. 2017, *ApJL* 851, L5; Fitzsimmons et al. 2018, *Nat. Astron.* 2, 133). Despite no signs of mass loss, ’Oumuamua displayed unexpected orbital anomalies, consistent with an anti-Sunward non-gravitational force (Micheli et al. 2018, *Nature* 559, 223) as strong as the strongest non-gravitational forces ever measured in Solar System comets. This suggested comet-like water-ice outgassing as the possible cause (Micheli et al. 2018). However, the proposed explanation is difficult to reconcile with the absent signs of mass loss, and it could not be properly tested given the poor observational limits on the water-ice outgassing.

To date, the most meaningful upper limit on the water production rate of ’Oumuamua was obtained from the non-detection of the 18-cm radio lines of OH using the Green Bank Telescope (Park et al. 2018, *AJ* 155, 185). Unfortunately, this observation was too brief (4 hours) and made too late (more than 3 weeks after the discovery of ’Oumuamua, when the object was already 1.8 au from the Sun and 1.1 au from the Earth), resulting in an insufficient sensitivity to address the problem of the object’s non-gravitational acceleration. Other limits, estimated indirectly from empirical relations (e. g. Hui & Knight 2019, *AJ* 158, 256) are inherently irrelevant, as they assume a typical cometary composition.

Potentially, the most promising instrument for the detection of water on ’Oumuamua is Solar Wind ANisotropies (SWAN) on the SOlar and Heliospheric Observatory (SOHO). SWAN is an all-sky mapper of hydrogen in the ultra-luminous Lyman alpha line, which is also an excellent tracer of cometary water (e. g. Combi et al. 2021, *Icarus* 365, 114509). The instrument provides unique access to daily measurements of the hydrogen emission, including pre- and post-discovery data for the positions of ’Oumuamua, when the object was relatively close to the Sun and the spacecraft (minimum distances of 0.46 au and 0.17 au, respectively). Based on the SOHO/SWAN observations, we will present the new most rigorous upper limit on the water production rate of ’Oumuamua, which is an order of magnitude lower than the best previous estimates actually sensitive to water. Most significantly, our limit enables us to discuss the hypothesized water-driven cause of the non-gravitational acceleration [5], the most recent concept of H_2O and H_2 emission (Bergner & Seligman 2023, *Nature* 615, 610), as well as the more exotic scenario of a hydrogen iceberg (Seligman et al. 2020, *ApJL* 896, L8). Our result supports the view that ’Oumuamua is unlike any object ever seen before.

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NOTES

Meteoroid mass estimation based on well-known atmospheric impacts

Anghel, S.[1,2*], Birlan, M.[1,2], and Nedelcu, D.A.[1,2]
[1]Astronomical Institute of the Romanian Academy, Romania, (Simon.Anghel@astro.ro), [2]IMCCE, Observatoire de Paris, France

Cosmic objects are impacting the Earth's atmosphere on a daily basis. Due to their small size, these meteoroids cannot be seen before interacting with the air particles. Thus, to better constrain the size of an impactor, we need calibrated multi-detector observations, combined with state-of-the-art theoretical models. To achieve this goal, multiple teams have set up networks (e. g. Colas et al. 2020; Pilger et al. 2020 and the references therein). In this study we explore several published techniques of measuring the pre-entry mass of meteoroids with well-known trajectory (also a subject of meteorite recoveries), at the source of ton TNT-scale atmospheric impacts. On this scale, the fireball is less likely to cause an airwave signal detectable on multiple specialized stations, or the estimation methods carry high uncertainty. Thus, in this analysis we focus on the optical energy signature of the objects. Most of the objects did have an estimate of the radiated light, hence, this was obtained via digitization from the published light curve. Next, the given velocity and mass, has allowed to derive a relation between the radiated light and the object's kinetic energy (Anghel et al. 2021). This, in turn will help cross-calibrate other methods of estimating the source energy, allowing to further constrain the size-frequency distribution of atmospheric impacts.

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NOTES

Wednesday 6th

Comets are Fragments: What the Kuiper Belt Size Distribution Tells Us About Its Collisional Evolution

Marschall, R.[1*]
[1]ICNRS, Observatoire de la Côte d'Azur, Laboratoire J.-L. Lagrange CS 34229 06304 Nice Cedex 4, France, (raphael.marschall@oca.eu)

There is a general consensus that cometesimals formed in an original reservoir, the primordial Kuiper belt (PKB), located between 20–40 au from the Sun [e. g., 1]. From there, they were scattered into the current trans-Neptunian region. From that region, the so-called scattered disk acts as the source reservoir for Jupiter family comets, JFCs [e. g., 2]. Current planetesimal formation models predict an initial Gaussian size distribution centered around $D = 100\,\mathrm{km}$ [e. g., 5–7]. Therefore, the question arises if such an initial size frequency distribution (SFD) of the PKB can reproduce the observational constraints of the current Kuiper belt. Indeed, I will argue that the collisional evolution of the PKB based on planetesimal formation models will evolve into a SFD that is consistent with (i) crater SFDs on icy satellites and KBOs [e. g., 9–12], and (ii) observed SFDs of populations derived from the PKB (e. g., Jupiter's Trojans) [13–14]. This suggests that comets formed large. But, the fact that current comets mostly have diameters between 1–5 km implies that these result from disruptions. I will discuss the fraction of comets that form through disruption and the implication of such a formation model.

NOTES

The Comet Interceptor Mission

Tubiana, C.[1*] on behalf of the Comet Interceptor team
[1] 1INAF-Istituto di Astrofisica e Planetologia Spaziali, Via del Fosso del Cavaliere 100, Roma, Italy, (cecilia.tubiana@inaf.it)

Comets are the most pristine objects in our Solar System. Having spent most of their life at large distance from the Sun, where they remained mostly unaffected by solar radiation, comets are the most unaltered remnants from the era of planet formation.

In recent decades great progress has been made in understanding these enigmatic objects through a series of spacecraft missions to short-period comets. In particular the European Space Agency (ESA) Rosetta mission Rosetta increased our knowledge about comets.

However, short-period comets have encountered the Sun many times, resulting in a significant surface evolution with each perihelion passage. One of the most striking results of Rosetta was that a good fraction of the material lifted off by activity falls back to the comet surface, re-blanketing the Northern hemisphere.

To better understand the conditions at the time of Solar System formation, we need to study comets which are approaching small heliocentric distances for the first time and are, therefore, less altered.

In June 2019, a multi-spacecraft project – Comet Interceptor – was selected by the European Space Agency (ESA) as its next planetary mission, and the first in its new class of Fast (F) projects [1]. ESA adopted Comet Interceptor in June 2022. The mission's primary science goal is to characterize, for the first time, a long-period comet – preferably one which is dynamically new – or an interstellar object. An encounter with a comet approaching the Sun for the first time will provide valuable data to complement that from all previous comet missions: the surface of such an object would be being heated to temperatures above the its constituent ices' sublimation point for the first time since its formation. The target of this mission is still unknown. In fact, Comet Interceptor will be designed and launched before its target is discovered. Afterwards, the spacecraft will wait in a parking orbit around the Sun-Earth L2 point, where it can station-keep with very little fuel, until a reachable LPC is found. The spacecraft will depart L2 to encounter the comet at a distance from the Sun of around 1 au, following a cruise period of up to 3 years. Even with this technique, the target comet needs to be discovered inbound at a relatively large distance, to give sufficient time to characterize its orbit and activity levels, and for the spacecraft to reach the encounter position.

We will present here an overview of the mission and its science goals.

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NOTES

Consequences for Solar System Formation and Evolution of the Early Activity & Removal of Bulk Hypervolatile CO, N_2, and CH_4 Ices by Evaporative Sublimation from Small Bodies

Lisse, C.M.[1*], Steckloff, J.K.[2], Prialnik, D.[3], Young, L.A.[4], and Gladstone, G.R.[4]
[1]Johns Hopkins University Applied Physics Lab, USA, (carey.lisse@jhuapl.edu), [2]PSI, USA, [3]Tel Aviv University, Israel, [4]SwRI, USA

We use laboratory measurements and modeling of the thermal behavior of the cryogenic ices CO, N_2, and CH_4 to argue that they are short lived in bulk form in small planetesimals where gravity is unimportant in binding them, evaporating within the first 10's of Myrs after disk-clearing in the early solar system [1-4]. Coupled with telescopic observations of the limited locations of hypervolatiles CO, N_2, and CH_4 in the modern solar system, we use this to show that: (1) MU69/Arrokoth was non-active during the New Horizons flyby of 01 Jan 2019 [2-5]; (2) Newly fragmented/disrupted SP comets do not show sudden outbursts of CO, N_2, or CH_4 [2]; (3) Large dwarf planet Pluto either formed very quickly, within $\sim$30 Myr, or is thoroughly differentiated throughout [2]; (4) The Oort Cloud, constructed $\sim$1 Gyr after the CAI's, should contain almost no hypervolatile dominated comets, but the few that are, like C/2016 R2, C/2017 K2, and C/UN271 reflect best the volatile abundances of the PPD [6]; (5) The terrestrial planet atmospheres, which formed much later than 30 Myr, are derived from NH_3 and not N_2 ices [7-8]; (6) Active Centaurs (actually recently perturbed KBOs) like 29P/SW-1 are driven by amorphous -> crystalline water ice conversion [9-11]; (7) The Jovian Trojans are a separately evolved 2-color population of relic water ice planetesimals with surfaces controlled by slow desiccation and impacts [11]; and (8) Phaethon's extremely blue color can be explained by a similar process causing repeated loss of nFe0 and refractory organic "ice" reddening agents.

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NOTES

Identification of Targets for ESA's Comet Interceptor Mission

Snodgrass, C.[1*], Sánchez, J.-P.[2], Knight, M. M.[3], Micheli, M.[4], Schwamb, M.[5], Guilbert-Lepoutre, A.[6], Holt, C.[7], Biver, N.[8], Inno, L.[9], Kokotanekova, R.[10], La Forgia, F.[11], Mazzotta Epifani, E.[12], Ootsubo, T.[13], Jones, G. H.[14], Tubiana, C.[15], Corral Van Damme, C.[4], and Kueppers, M.[4]

[1]University of Edinburgh, (csn@roe.ac.uk), [2]Institut Supérieur de l'Aéronautique et de l'Espace (ISAE-SUPAERO), France, [3]United States Naval Academy, USA, [4]EuropeanSpace Agency, [5]Queen's University Belfast, UK, [6]CNRS/Université de Lyon, France, [7]University of Maryland, USA, [8]LESIA, Observatoire de Paris, France, [9]Parthenope University of Naples, Italy, [10]National Astronomical Observatory, Bulgaria, [11]University of Padova, Italy, [12]INAF-Osservatorio Astronomico di Roma, Italy, [13]National Astronomical Observatory of Japan, Japan, [14]Mullard Space Science Laboratory, University College London, UK, [15]INAF-Istituto di Astrofísica e Planetologia Spaziali, Rome, Italy.

Comet Interceptor was selected by ESA in 2019 and is due to launch in 2029, to perform a fly-by of a yet-to-be-discovered comet in the 2030s. It will do this to perform a first encounter with a relatively pristine Long Period Comet entering the inner Solar System for the first time. The mission is unique in that it will be designed, built, and possibly even launched before its target is known. The spacecraft will wait in space, in a halo orbit around the Sun-Earth L2 point, between launch and the date it needs to depart to reach its interception point with its target comet. During the fly-by the main spacecraft will perform remote sensing and in situ measurements from a relatively safe distance, with a closest approach of about 1000 km, while two deployable small-sat probes will venture closer. The probes are supplied by JAXA and ESA and are designed to be expendable and short-lived, transmitting the data they collect back to the main spacecraft for storage and subsequent downlink to Earth over a period of months after the fly-by.

To enable spacecraft design within the mission budget and schedule constraints, a series of requirements are imposed on the choice of comet. For thermal design and energy Δv reasons the spacecraft can only encounter its comet within a range between 0.9 and 1.2 au from the Sun, and close to the ecliptic plane, which defines a flattened torus of possible comet encounter locations. The target comet must therefore have an orbit with perihelion distance below 1.2 au and a node within $0.9 - 1.2$ au. We further require the relative velocity between the spacecraft and comet at the fly-by to be < 70 km/s and at an angle towards/away from the Sun of > 45 degrees, for safety against dust impacts, and for thermal and power reasons and remote sensing instruments Sun avoidance, respectively. Slower encounters, i. e. avoiding retrograde orbits that give the highest velocities, and encounters at the pre-perihelion node are strongly preferred, but the limits are based on the Giotto encounter with comet Halley as a 'worst case'. We also therefore require a target with total activity at a similar level, or less, than Halley, but have to trade safety of the spacecraft with expected signal levels for in situ instruments when considering the expected activity level of the comet. A comet encounter that is relatively close to Earth is much better than one on the far side of the Sun, for both data transfer and complementary ground-based observations.

We find a high probability that there should be reachable comets within these constraints. This depends on exactly how much warning time we have between discovery of the comet and needing to depart L2, as longer cruise times give a wider range of possible encounter locations. This in turn depends on the size and intrinsic activity level of the comet, how its brightness evolves with distance from the Sun, and the sensitivity and cadence of the survey that detects the comet (which will probably be the Vera C. Rubin observatory's LSST). In this presentation we will describe our studies of distant cometary activity, simulations of future comet discovery, and how we plan to characterize and prioritize potential targets for Comet Interceptor in the coming years.

NOTES

Linking the gas and dust activity of distant comet 29P/Schwassmann-Wachmann 1

Bockelée-Morvan, D.[1*], Biver, N.[1], Schambeau, C. A.[2]
[1]LESIA, Observatoire de Paris, France, (dominique.bockelee@obspm.fr), [2]Florida Space Institute, University of Central Florida, USA

29P/Schwassmann-Wachmann 1 is a distant Centaur/comet, showing persistent CO-driven activity and frequent outbursts. It is a fascinating object for understanding distant cometary activity and evolutionary processes that affect the surface and interior of Centaurs. I will review recent progresses ([1]) made regarding: 1) the composition and properties of its atmosphere, 2) the origin of gas phase species, 3) the CO activity during outbursting stages and how it correlates with dust activity, and 4) the origin of the outbursts which may point to local heterogeneities on the surface.

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NOTES

Dependence of modelled cometary gas production on the layer transport properties

Skorov, Yu[1,2*], Reshetnyk, V.[3,4], Markkanen, J.[1,2], Mottola, S.[5], Küppers, M.[6], Hartogh, P.[1]
[1]Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, D-37077 Göttingen, Germany, [2]Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig, Mendelssohnstr. 3, D-38106 Braunschweig, Germany, [3]Taras Shevchenko National University of Kyiv, Glushkova ave. 2, Kyiv, Ukraine, [4]Main Astronomical Observatory of National Academy of Science of Ukraine, Akademika Zabolotnoho Str. 27, 03680 Kyiv, Ukraine, [5]DLR Institute of Planetary Research, Rutherfordstrasse, 2, 12489 Berlin, Germany, [6]European Space Agency (ESA), ESAC, Camino Bajo del Castillo s/n, 28692 Villanueva de la Cañada, Madrid, Spain

We present a review of the latest results focused on the study of various transport and thermophysical characteristics of porous heterogeneous media. These studies are directly related to the analysis of astronomical observations of the activity of comets, both on the ground and with spacecraft.

Explanation of the observed gas activity based on the parameters of the comet's nucleus is not an obvious matter. Solutions based on specific thermal models can be obtained, but the use of arbitrary values for poorly known model parameters is always required.

The standard approach to obtaining knowledge about the properties of the surface layer of a comet from observations of gas production consists of two stages. First, various thermophysical models are used to calculate gas production for a few sets of parameters. Second, a comparison of observations and theoretical predictions is performed. This approach is complicated because the values of many model characteristics are known only approximately. Therefore, it is necessary to investigate the sensitivity of the simulated outgassing to variations in the properties of the surface layer.

In the set of recent research, we studied the dependence of gas activity on the various model parameters and evaluated their role. Model porous dust layers of diverse structures are considered. The different mechanisms of thermal conductivity were studied to estimate the possible changes in effective thermal conductivity. This problem was recently considered by us for aggregates up to tens of microns in size. For millimetre-size aggregates, a qualitative extension of the method used to model the structural characteristics of the layer was done this year. The simulation results were included in modified thermal models that explicitly include the resistance of the dust layer to the gas flow. Sublimation of water ice and supervolatiles (CO_2 and CO) was tested at different heliocentric distances.

It is shown that when sublimation is the main energy sink, the role of uncertainties in the layer structure is small. As the relative contribution of sublimation decreases, the scatter of solutions reaches tens of percent. Expected large uncertainties in effective thermal conductivity can also significantly change gas production. The performed analysis shows that, despite the narrowing of the range of parameters based on the results of the Rosetta mission, the inevitable uncertainty in the values of some model parameters (for example, thermal conductivity) smears the theoretical estimates of the simulation. Instead of presenting a narrow set of specific solutions, it is desirable to analyze the full range of possible solutions.

NOTES

Thursday 7th

Active Asteroids: A Review of Recent Studies and Future Prospects

Hsieh, H.H.[1,2*]
[1]Planetary Science Institute, United States of America, (hhsieh@psi.edu), [2]Academia Sinica Institute of Astronomy and Astrophysics, Taiwan

Active asteroids are small solar system bodies that exhibit comet-like mass loss yet have asteroid-like orbits in the inner solar system. A key sub-group of the active asteroids, the main-belt comets, which are active asteroids in the main asteroid belt whose mass loss is specifically driven by the sublimation of volatile ice, was first recognized in 2006, but since then, the range of known mechanisms that can produce visible mass loss by objects on asteroidal orbits has expanded to include processes like impact disruptions, rotational destabilization, and others. Main-belt comets represent a previously unrecognized reservoir of volatile material in the inner solar system, and thus present opportunities for various exciting research efforts related to advancing our understanding of the volatile content of the protosolar disk, the thermal and dynamical evolution of icy bodies over the age of the solar system, and the primordial delivery of water and other volatile material to the terrestrial planets. Meanwhile, active asteroids whose mass loss is caused by processes like impact disruptions and rotational destabilization events, or disrupted asteroids, offer opportunities to study these processes in real time in the real world, rather than only being able to study them using theoretical or computational models, or in laboratory experiments.

In this presentation, I will review the current state of knowledge about active asteroids and the opportunities they offer for advancing our understanding of both the early and modern-day solar system. I will also summarize results of key recent observational, dynamical, and thermal modeling studies and their implications, and discuss future prospects for the exploration of this relatively recently recognized class of small solar system bodies via ground- and space-based observing, theoretical studies, laboratory experiments, and targeted missions.

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Active asteroids, natural and artificial: The DART mission

Moreno, F.[1]
[1]Instituto de Astrofísica de Andalucía, CSIC, Granada, Spain

In this talk I will review the physical properties of some observed active asteroids using Monte Carlo techniques to capture the dust tail brightness profiles. I will describe first some of those natural active asteroids observed with the 10.4-m Gran Telescopio Canarias since 2010 [1], and then I will describe the dust properties of the ejecta resulting from the collision of the NASA/DART spacecraft on the secondary component of the (65803) Didymos system through a detailed dynamical model to compute the dust grain orbital evolution in the complex gravity field of the two binary components [2,3].

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NOTES

Activity of Main-Belt Comet 324P/La Sagra

Mastropietro, M.[1,2*], Kim, Y.[1,3], Hsieh, H.H.[4], and Agarwal, A.[1,2]
[1]Institut für Geophysik und Extraterrestrische Physik, Technische Universität Braunschweig, Germany, (m.mastropietro@tu-braunschweig.de), [2]Max Planck Institute for Solar System Research, Göttingen, Germany, [3]University of Arizona, Tucson, USA, [4]Planetary Science Institute, Tucson, USA

Main-belt comets (MBCs) are a subclass of active asteroids that undergo sublimation of ice [1]. Among these MBCs is the main-belt asteroid 324P/La Sagra (P/2010 R2), which has been observed exhibiting repeated dust emission during subsequent perihelion passages. The nature of its dust emission implies that it is most likely driven by water ice sublimation, a characteristic feature of MBCs.

This research presents the photometric analysis of 324P/La Sagra. We analyze archival data of this object from 2010 to 2021, collected from various telescopes in optical and infrared bands, to study its activity. The photometric analysis of the optical data shows that the absolute R-band magnitudes and the estimated dust masses of 324P/La Sagra agree with previous studies. We confirm a significant decrease in its activity during the 2015 perihelion passage compared to its previous perihelion passage in 2010. We also investigate the most recent perihelion passage in 2021, finding that its activity decreased compared to that in 2015. Additionally, we determine the geometric albedo of the cometary grains in 324P/La Sagra by combining optical and infrared data. Our analysis reveals a z-band geometric albedo of 0.065 ± 0.030, consistent with the typical low albedo classification associated with 324P/La Sagra [2].

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NOTES

Long-term Evolution of the Dimorphos Tail Observed by Hubble Space Telescope

Li, J.-Y.[1*], Cheng, A.F.[2], Chesley, S.[3], Fahnestock, E.G.[3], Farnham, T.L.[4], Hirabayashi, M.[5], Knight, M.M.[6], Kolokolova, L.[4], Moreno, F.[7], Rivkin, A.S.[2], Sunshine, J.M.[4], Tancredi, G.[8], Thomas, C.A.[9], Weaver, H.A.[2], Zhang, Y.[4], and the DART Investigation Team

[1]Planetary Science Institute, USA, (jyli@psi.edu), [2]The Johns Hopkins University Applied Physics Laboratory, USA, [3]Jet Propulsion Laboratory, California Institute of Technology, USA, [4]University of Maryland College Park, USA, [5]Auburn University, USA, [6]United States Naval Academy, USA, [7]Instituto de Astrofísica de Andalucía, CSIC, Spain, [8]Facultad de Ciencias, Uruguay, [9]Northern Arizona University, USA

The successful impact of the DART (Double Asteroid Redirection Test) spacecraft into Dimorphos [1] excavated an ejecta composed of dust particles from µm to cm in size [2] with embedded boulders up to $\sim$2 m observed [3]. A tail formed from the low-speed ejecta dust due to solar radiation pressure (SRP) [2, 4]. Depending on the particle size, slow ejecta dust could be trapped in orbit around Didymos before they are slowly pushed out of the binary system by SRP and feed into the tail [5]. Small particles could also be lifted and released from the binary system due to re-impact of the ejecta onto Didymos and Dimorphos, especially with the fast rotation of Didymos [6]. Long-term monitoring of the tail characterizes the large dust particles of a few to tens of cm in size, and probe the dynamic process and re-impact released dust in the binary system. Additionally, it will provide us with a unique context to interpret active asteroids through the Dimorphos tail that has been produced by a controlled impact experiment [2, 7].

We monitored the evolution of the tail using the Hubble Space Telescope from November 30, 2022, through June 2023 with the WFC3/UVIS. The tail morphology evolution was consistent with dust released within two weeks after the DART impact. The brightness of the tail faded following a broken exponential model. The evolution of the brightness profile along the tail suggested increasing power law slopes of up to -4.7 for the particle size distribution up to 3 cm-radius particles, compared to -3.7 for a few mm to cm particles and -2.7 for smaller particles as measured from the images collected shortly after impact [2]. The increasing slope indicated a depletion of cm and larger particles in the tail. A diffuse dust cloud was visible to the south of the main tail, consistent with sub-mm to a few mm particles released up to 8 weeks after impact. Preliminary analysis suggested that the diffuse cloud contains both the temporarily trapped particles in the binary system slowly released by SRP and dust lifted by re-impact of the ejecta onto Didymos and Dimorphos. We will discuss the results from these observations and the implications for active asteroids.

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NOTES

Scattering and absorption of light in asteroid regoliths

Muinonen, K.[1]
[1]Department of Physics, University of Helsinki, Finland, (karri.muinonen@helsinki.fi)

Surfaces of asteroids are composed of regoliths, that is, loose layers of dust particles covering more solid material. Vast majority of knowledge on the asteroids is accrued remotely based on how light is scattered and absorbed in their surfaces. Thus, accurate theoretical, numerical, and experimental scattering methods for small particles and regoliths of small particles are a key for the retrieval of asteroid physical and chemical properties.

The photometric and polarimetric phase curves of an asteroid describe, respectively, the dependences of the asteroid's disk-integrated brightness and degree of linear polarization on the solar phase angle, the angle between the Sun and the observer as seen from the object. On one hand, different types of photometric phase curves can be derived from lightcurve observations, such as the sparse lightcurves observed by the ongoing ESA Gaia space telescope mission. In particular, lightcurve inversion allows for the retrieval of intrinsic photometric phase curves, from which the effects due to the asteroid's nonspherical shape and the illumination and observation geometry, affected by the rotational phase and pole orientation, have been removed. On the other hand, polarimetric phase curves are insensitive to the shape and rotational characteristics of the asteroid. The asteroid's spectrum at wavelengths from the ultraviolet through the visible to the near-infrared provides compositional information, based on the absorption bands of the spectrum, about the object in terms of its mineralogy. The spectrum depends on the phase angle, too.

Synoptic scattering modeling, accounting for shadowing amongst the particles, a first-order multiple-scattering mechanism, and the higher-order mechanism of coherent backscattering, will here be offered for the photometric and polarimetric phase curves of asteroids. First, scattering matrices of nonspherical particle ensembles are analytically decomposed into sums of four pure Mueller matrices. Of these matrices, there is a single matrix that qualifies as a pure scattering matrix, whereas the remaining three matrices represent other classes of pure Mueller matrices. It follows that the decomposition allows for radiative-transfer coherent-backscattering computations for regoliths of nonspherical particles. The modeling allows for the interpretation of both the photometric opposition effect and the negative degree of linear polarization near opposition that are ubiquitous phenomena observed for asteroids. The former phenomenon is a nonlinear increase of the object's disk-integrated brightness towards the opposition (zero phase angle) in the magnitude range, whereas the latter is a predominating linear polarization parallel to the scattering plane defined by the Sun, object, and the observer. Preliminary applications will be presented for a number of asteroids representing different taxonomical classes.

NOTES

JWST Observations of Centaurs: CO_2 and CO Production Rates

McKay, A.J.[1*], Harrington-Pinto, O.[2], Faggi, S.[3,4], Villanueva, G.L.[3], Kelley, M.S.[5], Womack, M.[6], Schambeau, C.[2], Feaga, L.[5], DiSanti, M.A.[3], Fernandez, Y.[2], Bauer, J.[5], and Wierzchos, K.[7]
[1]Appalachian State University (mckayaj@appstate.edu), [2]University of Central Florida, [3]NASA Goddard Space Flight Center, [4]American University, [5]University of Maryland, [6]National Science Foundation, [7]University of Arizona

Introduction: Centaurs are primitive leftovers from the formation of the solar system and are thought to be the dynamical precursors to Jupiter Family Comets (JFCs). Therefore, their volatile composition holds precious clues to the physics and chemistry of the early solar system as well as the degree of compositional evolution experienced by JFCs. However, their large heliocentric distances make observations of volatile gases in centaurs challenging. Moreover, the mechanisms driving Centaur activity are still poorly understood. Hyper-volatile species (e. g., CO, CO_2) have been considered possible drivers of their outgassing, but crystallization of amorphous water ice is another possibility.

JWST Centaur Program: JWST GO Program 2416 (PI Adam McKay) is observing active centaurs with the NIRSpec instrument to characterize their volatile composition, specifically in terms of H_2O, CO_2, and CO. Five of our six targets have been observed as of May 2023. We will present an overview of this program to date, with additional focus on 29P/Schwassmann-Wachmann 1 (SW1). While interesting as an active Centaur, SW1 is also compelling as an individual object, experiencing quasi-periodic outbursts in brightness whose mechanism is not fully understood. SW1 is also currently located in a potential dynamical gateway for newly active JFCs (Sarid et al. 2019). The centaur may consequently be in the early stages of the onset of activity, making it an even more compelling object of study.

Observations: Spectra of our target centaurs were obtained with JWST NIRSpec in PRISM IFU mode, with a wavelength coverage of 0.59 to 5.29 microns, covering the fundamental bands of H_2O, CO_2, and CO, their isotopologues, CO+, as well as ice absorption features from these species.

Overview of Results: The first object observed was 39P/Oterma, and our observations provided the first detection of CO_2 in a centaur. Additional objects observed were C/2019 LD2 (ATLAS), C/2014 OG392 (PanSTARRS), and 423P/LONEOS, and analysis of these data are ongoing.

29P/SW1 Results: We detected both CO and CO_2 in SW1, providing the first detection of CO_2 in SW1. Preliminary analysis indicates a CO_2/CO ratio $<< 1$, in qualitative agreement with the AKARI upper limit and inferred ratio from Harrington-Pinto et al. 2022. The spatial distributions of CO_2 and CO also appear different, with the CO_2 showing a "hook" feature that is similar to that sometimes observed for the dust coma, while CO shows a more rectangular morphology. There are also several candidate ice absorption features present in the spectrum. We will present an overview of all these results pertaining to SW1, compare to previous observations of SW1 and other centaurs, and discuss future work.

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NOTES

A Hundred Sleeping Beasts: The Lack of Activity Among Centaurs Between Jupiter and Uranus

Lilly, E.[1*], Jevčák, P.[2], Schambeau, C.[3], Šilha, J.[2], Hsieh, H.[1], Steckloff, J.[1], Wainscoat, R.J.[4], Weryk, R.[4]
[1]Planetary Science Institute, USA, (elilly@psi.edu), [2]Comenius University, Slovakia, [3]University of Central Florida, USA, [4]University of Hawaii, USA

Here we present an observational and thermo-dynamical study of 99 Centaurs aimed at identifying and characterizing active objects beyond the orbit of Jupiter. We have conducted a dedicated snapshot survey with the Gemini North and South telescopes between 2020 and 2022. Our targets have wide range of perihelion distances and were either nearing or just passed their perihelion during our observing campaign, possibly experiencing the best conditions promoting activity. However, only one Centaur in our sample – C/2014 OG_{392} (PANSTARRS) appeared active at the time of our observations in 2020B.

Our numerical integrations show that the orbits of the majority of our targets evolved interior to $\sim$14 AU over the past 5000 years, which is a region where several possible processes could trigger phase transitions of volatiles leading to outgassing and dust lofting [1] [2]. The apparent inactivity of inspected Centaurs, including objects with perihelia near Jupiter and in the JFC Gateway [3] indicates their dust production is either below our detection limit or that the objects are dormant. The dynamical history of our targets apart from C/2014 OG_{392} doesn't show abrupt changes in perihelion distance and semi-major axis typical for active Centaurs and JFCs, adding further evidence that the past orbital evolution plays a critical role in the thermal processing of Centaurs and JFCs [4] and their potential for onset of cometary activity [5].

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NOTES

Dust tail simulation for asteroid 6478 Gault

Reshetnyk, V.[1,2*], Ivanova, O.[2,3], Skorov, Yu.[4]
[1]National Taras Schevchenko University of Kyiv, Ukraine, [2]Main astronomical observatory of National academy of sciences of Ukraine, [3]Astronomical Institute of the Slovak Academy of Science, [4]IGEP TU, Braunschweig, Germany

Asteroid 6478 Gault shows not comet-like dust activity. In general the reasons for the ejection of dust particles from the surface of asteroids are not always clear. There were proposed different mechanisms. In our model the source of activity was a centrifugal force. We simulated the motion of carbon and silicate dust particles of various sizes. The minimum size of dust particle is $0.1\,\mu$m, maximal size 0.2 mm. Optical parameters were calculated for each dust particle from Mie theory. The radius and mass of asteroid Gault were taken as input data for the simulation. We consider two different type of dust source: point and extended active equatorial region. The solar radiation pressure was calculated based on the actual position of asteroid Gault at a given moment. The map of dust particles trajectories was obtained. Synthetic photometric images of the tail were constructed based on the obtained trajectories of the dust particles. The simulation was carried out for different orientation of the axis of rotation and the period of the asteroid's rotation. There was showed that the shape of coma depends on the orientation of the rotation axis. The radial profile along the tail is not monotonic especially for point-like source. Rotation of the asteroid can explain spatial oscillation of the brightness in the tail.

NOTES

The DESTINY+ Mission to the Active Asteroid (3200) Phaethon

Krüger, H.[1], and Masanori Kobayashi, Ralf Srama, Tomoko Arai, Jan Gläser, Jon Hillier, Takayuki Hirai, Stephan Ingerl, Motoo Ito, Nozair Khawaja, Hiroshi Kimura, Yanwei Li, Frank Postberg, Sho Sasaki, Jürgen Schmidt, Jonas Simolka, Maximilian Sommer, Veerle Sterken, Heiko Strack, Peter Strub, Mario Trieloff, Hikaru Yabuta, and the DESTINY+ dust science team
[1]Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany (krueger@mps.mpg.de)

The DESTINY+ spacecraft (Demonstration and Experiment of Space Technology for INterplanetary voYage with Phaethon fLyby and dUst Science) will be launched by the Japanese Space Agency JAXA in 2024. The main mission target will be the active asteroid (3200) Phaethon, with a close flyby in 2028. Together with two cameras on board, the DESTINY+ Dust Analyzer (DDA) will perform close observations of the active asteroid to solve essential questions related to the evolution of the inner Solar System, including heating processes and compositional evolution of small solar system objects. Phaethon is believed to be the parent body of the Geminids meteor shower and may be a comet-asteroid transition object. Such objects can likely provide information to better understand the nature and origin of mass accreted on to Earth.

The DDA instrument is an upgrade of the Cassini Cosmic Dust Analyzer (CDA) which very successfully investigated the dust environment of the Saturnian system. DDA is an impact ionization time-of-flight mass spectrometer with integrated trajectory sensor, which will analyse sub-micrometer and micrometer sized dust particles. The instrument will measure the particle composition (mass resolution $m/\Delta m \approx 100-150$), mass, electrical charge, impact velocity (about 10% accuracy), and impact direction (about 10° accuracy). In addition to dust analysis in the vicinity of Phaethon during the close flyby at this small asteroid, DDA will continuously measure dust in interplanetary space in the spatial region between approximately 0.9 and 1.1 AU during the approximately two years spanning cruise phase from Earth to Phaethon. We give an overview of the DESTINY+ mission, the Dust Analyzer DDA and the science goals for the analysis of Phaethon dust as well as interplanetary and interstellar dust to be measured en route to the active asteroid.

NOTES

Missions to Study Interstellar Objects at Various Heliocentric Distances

Hein, A. M.[1*], Perakis, N.[1,5*], Marshall Eubanks, T.[2], Lingam, M.[3], Hibberd, A.[1], Fries, D.[1], Schneider, J.[4], Kervella, P.[6], Kennedy, R.[1], Dachwald, B.[7]

[1]Initiative for Interstellar Studies (i4is), 27/29 South Lambeth Road, London SW8 1SZ, United Kingdom, (andreas.hein@i4is.org), [2]Space Initiatives Inc, Palm Bay, FL 32907, USA, (tme@space-initiatives.com), [3]Department of Aerospace, Physics and Space Sciences, Florida Institute of Technology, Melbourne, FL 32901, USA, (mlingam@fit.edu), [4]Observatoire de Paris – LUTH, 92190 Meudon, France, (jean.schneider@obspm.fr), [5]Department of space propulsion, Technical University of Munich, Germany, (nikolaos.perakis@tum.de), [6]LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris, 5 place Jules Janssen, 92195 Meudon, France, (Pierre.Kervella@obspm.fr), [7]Faculty of Aerospace Engineering, FH Aachen University of Applied Sciences, 52064 Aachen, Germany, (Dachwald@fh-aachen.de)

The recently discovered first hyperbolic objects passing through the Solar System, 1I/'Oumuamua and 2I/Borisov, have raised the question about near term missions to Interstellar Objects. In situ spacecraft exploration of these objects will allow the direct determination of both their structure and their chemical and isotopic composition, enabling an entirely new way of studying small bodies from outside our solar system. In this paper, we map various Interstellar Object classes to mission types, demonstrating that missions to a range of Interstellar Object classes are feasible, using existing or near-term technology. The Interstellar Object classes cover those flying in- and out of our Solar System and captured ones. We identify a total of 9 Interstellar Object classes. We describe flyby, rendezvous and sample return missions to interstellar objects, showing various ways to explore these bodies characterizing their surface, dynamics, structure and composition. Their direct exploration will constrain their formation and history, situating them within the dynamical and chemical evolution of the Galaxy. These mission types also provide the opportunity to explore solar system bodies and perform measurements in the far outer solar system.

NOTES

Detection of Cometary Activity on Centaur 2014 OG_{392}

Jevčák, P.[1*], Lilly, E.[2], and Šilha, J.[1]
[1]Comenius University, Slovakia, (peter.jevcak@fmph.uniba.sk), [2]Planetary Science Institute, USA

Centaurs are solar system small bodies orbiting in the giant planet region which were scattered inwards from their source population beyond Neptune. Some members of the population display comet-like activity even far beyond the orbit of Jupiter during their transition through the solar system, the source of which is not well understood. Most of them are too cold for activity at the observed levels to originate via the sublimation of water-ice. Super volatiles also cannot be the sole source of the activity, since they should drive the activity at much larger distances than observed.

Centaur 2014 OG_{392} is an active Centaur whose activity was detected at the distance 10 au from the Sun on images from the year 2017 [1]. We analyzed the Centaur using the images acquired with GMOS-N instrument located at Gemini North Observatory. Centaur was observed on two separate nights in the summer 2020. Our analysis confirmed the ongoing activity even 3 years after its first detection.

Centaur 2014 OG_{392} experienced a rapid orbital change approximately 160 years ago during a close encounter with Saturn. This change decreased semi-major axis and eccentricity, while perihelion distance of the Centaur stayed the same, making the orbit more circular than before. Decrease in semi-major axis can lead to an overall increase in the pre-orbit average surface temperature, which could translate into change in surface and subsurface thermal environment. Similar orbital changes – a-jumps, are common features in past orbital evolution of all active Centaurs and high-perihelion Jupiter Family Comets, and are speculated to be the triggers of cometary activity on Centaurs [2].

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NOTES

Characterizing Activity in Centaur-to-JFC Transition Object P/2019 LD_2

Fernandez, Y.R.[1*], Bolin, B.[2], Schambeau, C. A.[1], Bodewits, D.[3], Holt, T. R.[4], and Lisse, C. M.[5]
[1]Univ. of Central Florida, USA, (yan@ucf.edu), [2]NASA/Goddard Space Flight Center, USA, [3]Auburn Univ., USA, [4]U. Southern Queensland, Australia, [5]Johns Hopkins Univ. Applied Physics Lab., USA

Comet P/2019 LD_2 (ATLAS) (hereafter "LD2") is an active object that is currently in transition from a life beyond Jupiter as a Centaur to a new phase as a Jupiter-family comet (JFC) in the inner Solar System. While many known Centaurs transition on approximately million-year time scales, LD2 is doing it right now [1,2], moving from a "Gateway" orbit [3] that was until 2017 entirely beyond Jupiter to an orbit that by 2063 will be entirely interior to Jupiter. Studies of Centaurs, distant JFCs, and transition objects like LD2 can provide insight to the short-term evolutionary processes that primitive objects suffer while they are on the dynamical cascade through the Centaur region and into the inner Solar System [4,5]. This is particularly interesting in the case of objects for which cometary activity has begun while still in or near the Centaur region, since the driver of such activity likely differs from that of many JFCs (e. g. [6]). Surface properties of these bodies can be modified by their own ongoing activity far from the Sun in a way that can give clues about the nature of the activity and about the compositional/structural layering in the interior. Our overarching goal is to use the fortuitously-placed LD2 to investigate these questions.

In this presentation we focus on the continued characterization of LD2's nucleus and dust properties, as a follow-on to our earlier work [7]. We have LD2 visible-wavelength imaging and photometry from the HST, the Gemini Observatory, and the Palomar 5-meter telescope at 14 epochs in 2020–2023, when the comet had heliocentric distances from 4.85 to 5.26 au. (Perihelion was on April 10, 2020.) The excellent spatial resolution of the HST imaging of the coma and central condensation lets us use our empirical technique to photometrically extract the nucleus [e. g. 8]. The ground-based imaging datasets in Sloan bands provide us with the means to assess LD2's dust properties over time through an analysis of the photometry and morphology at each epoch. Importantly, our data cover a time interval after perihelion as the thermal pulse is propagating into the nucleus's interior, and this perihelion was closer than others that the comet had recently experienced. We will use the data to constrain the time evolution of dust production rate, coma dust grain size distribution, and dust color as the comet moves away from perihelion. Our presentation will summarize our dust and nucleus findings, as well as compare these to those reported in other published work [e. g. 9,10].

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NOTES

Physical properties of Centaur 174P/Echeclus: post perihelion follow up observations

Kulyk, I.[1*], Ivanova, O.[2], Luk'yanyk, I.[3]
[1]Main Astronomical Observatory of the National Academy of Sciences of Ukraine, (irynakulyk59@gmail.com), [2]Astronomical Institute, Slovak Academy of Sciences, (oivanova@astro.sk), [3]Astronomical Observatory of Taras Shevchenko National University of Kyiv, (igor.lukyanyk@gmail.com)

Centaur 174P/Echeclus, discovered in 2000 and initially designated as (60558) 2000 EC98 [1], has exhibited sporadic outburst activity over a wide range of heliocentric distances. The archive data also reveals a small cometary coma on pre-discovery images [2]. Since its discovery Echeclus has moved approximately three-quarters of the orbit, passing perihelion in April 2015. During this period four Echeclus' outbursts were detected. A number of important results on Echeclus were obtained from the previous observations: the 2005 Echeclus outburst was the largest one ever detected for a Centaur; no emission lines have been observed in the optical spectral range; unusual blue color of the dust coma and red nucleus surface was revealed during 2017 outburst; the amplitude of Echeclus' light curve varies along the orbit pointing out that a rotation axis is probably strongly inclined from the normal of its orbital plane; the upper limit on CO $J = 2 - 1$ emission line suggests that Echeclus can be a CO-deficient body [3,4 and references herein, 5].

Now Echeclus moves on its post-perihelion part of the orbit that has not been covered by observations yet. We present new results of a detailed photometric study of the post-perihelion Echeclus' images obtained with the 2-m Liverpool Telescope during 6 sequential nights in October 2019. Since there are no signs of physical activity of the target, we use the B, V, R, I images to calculate the normalized reflectivity gradients of its nucleus in the BV, VR, and RI spectral intervals and amplitudes of Echeclus' light curves in the different spectral bands. The time-series analysis applied to the light curves allows us to verify the rotation period obtained from the previous observations.

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NOTES

Radar observability of near-Earth objects using EISCAT 3D

Kastinen, D.[1*], Tveito, T.[2], Vierinen, J.[2] Granvik, M.[3,4]
[1]Swedish Institute of Space Physics (IRF), Sweden, (daniel.kastinen@irf.se), [2]Arctic University of Norway (UiT), Norway, [3]Luleå University of Technology (LTU), Sweden, [4]University of Helsinki, Finland

Radars are versatile tools within the field of near-Earth object (NEO) studies, for example radar observations can be used to estimate accurate orbital elements due to the high precision range and range rate measurables.

There is currently a 233 MHz, 4 MW, high-power, large-aperture radar, called EISCAT 3D, under construction in the Fenno-Scandinavian Arctic. The main objectives of this system are related to studies of processes in Earth's upper atmosphere and ionosphere. But, given its versatile design and high power it has the potential to also significantly contribute to NEO studies. To examine these possibilities, we have evaluated the EISCAT 3D observability of NEOs [1].

Three different populations were considered: 1) NEOs passing by Earth with a size distribution extrapolated from fireball statistics, 2) catalogued NEOs detected with ground-based optical telescopes, and 3) temporarily captured NEOs, i. e. minimoons. Two types of observation schemes were evaluated: serendipitous discovery and post-discovery tracking using a priori orbital elements.

The results indicate that 60–1200 objects per year, with diameters $D > 0.01$ m, can be discovered, while using the current NEO discovery rates, around 20 objects per year can be tracked post-discovery. Finally, using a theoretical minimoon population model, we estimated that approximately seven objects per year can be discovered while approximately 80–160 could be tracked post-discovery. These results indicate that observations from EISCAT 3D could complement the capabilities of dedicated planetary radars that are designed for that purpose, as well as serve as a novel source for NEO discoveries.

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NOTES

Tianwen-2 mission target asteroid (469219) 2016 HO_3: preliminary spectroscopic observation results from Gran Telescopio CANARIAS (GTC)

Bin, L.[1*], Chunlai, L.[1], Jianjun, L.[1], Xin, R.[1], Dawei, L.[1], Jishi, Z.[2], and Yan, G.[2]
[1]Key Laboratory of Lunar and Deep Space Exploration, National Astronomical Observatories,Chinese Academy of Sciences, Beijing 100101, China, (liub@nao.cas.cn), [2]Lunar Exploration and Space Engineering Center, Beijing 100190, China

Asteroid 2016 HO_3 is the nearest and most stable Earth quasi-satellite (C. de la Fuente Marcos and R. de la Fuente Marcos, 2016), it's also a potential target for future missions (Heiligers et al., 2019). China plans to launch a probe (Tianwen-2) to detect 2016 HO_3 around 2025 (Zhang, X. J. et al., 2019). It intends to complete 2016 HO_3's orbiting, sampling (touching, hovering, attachment) and samples return in one mission. Since asteroid 2016 HO_3 is too faint, it is difficult for small-aperture ground-based telescopes and space telescopes to observe, and large-aperture telescopes are needed. There are few ground-based observation data of asteroid 2016 HO_3, so the understanding of its surface physical properties, composition, and possible origin is still limited. In order to ensure a successful implementation of Tianwen-2 mission, it is necessary to conduct more ground-based observations of 2016 HO_3 with large aperture telescopes.

GTC, one of the largest and most advanced telescopes in the world, is used to make spectroscopic observations of 2016 HO_3. In order to obtain data with high signal-to-noise ratio, we obtained low-resolution spectra of 2016 HO_3 three times by OSIRIS spectrometer on June 2017, May 2018, and May 2019. During each observation, the exposure time is set 1800 seconds and 5 time observations in succession to obtain an average spectrum. The standard stars (SA110-361 and SA107) are also observed to calculate the reflectance ($400 \sim 1000$ nm) of 2016 HO_3. The possible taxonomic type of 2016 HO_3 is analyzed based on the Bus DeMeo asteroid taxonomy, and the results show that 2016 HO_3 is most likely A, L or Sv type, which is similar with the results of Benjamin et al. (2021). This result indicates that asteroid 2016 HO_3 is likely composed of silicate minerals, possibly rich in pyroxene and olivine.

Based on the abnormal "reddening" (with high spectral slope) spectral characteristics in the near infrared bands of 2016 HO_3, Benjamin et al. (2021) implies that 2016 HO_3 may be originated from lunar ejecta. In order to further constrain the possible origin of asteroid 2016 HO_3, we plan to use OSIRIS long slit spectrosocpy and the EMIR near-infrared imaging bands (Y, J, H, Ks) to observe the faint asteroid 2016 HO_3 and the possible cognates of 2020 PN_1 and 2020 PP_1. In early August this year, 2020 PN_1 and 2020 PP_1 are in the best observation period. During the conference, we may also introduce the preliminary OSIRIS and EMIR observation results of these two targets.

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NOTES

Bridging the Gap Between TNOs and JFCs: A Large and Long Investigation of Centaurs and Distantly Active Jupiter-Family Comets

Schambeau, C.A.[1], Fernandez, Y.R.[1], Lilly, E.[2], Beck, C.[1], Walker, S.[1], Micheli, M.[3], Jevčák, P.[4], Kareta, T.[5], Samarasinha, N.H.[2], Woodney, L.M.[6]
[1]University of Central Florida, Orlando, FL32826, (charles.schambeau@ucf.edu), [2]Planetary Science Institute, Tucson, AZ, [3]ESA NEO Coordination Centre, Frascati, Italy, [4]Comenius University Bratislava, Slovakia, [5]Lowell Observatory, Flagstaff, AZ, [6]California State University San Bernardino, San Bernardino, CA

Introduction: Centaurs are small icy bodies containing some of the least processed materials in our solar system. These materials provide a link to the initial protoplanetary physicochemical conditions during the onset of planetary accretion. Their short-lived ($\sim$10 Myr) chaotic orbits between Neptune and Jupiter [1] represent the intermediate step for the inward migration of an $\sim$4.5 Gyr-old cryogenically preserved Trans-Neptunian Object (TNO) in the dynamically excited Scattered Disk to an actively sublimating Jupiter family comet (JFC) with a short $\sim$0.4 Myr active lifetime [2]. A better understanding of the ongoing material processing in the Centaur region will provide insights into the material processing that occurs for this dynamically linked population of small icy bodies. We are working now to systematically study activity in Centaurs by characterizing the long-term dust comae activity behaviors for a population of $\sim$60 Centaur-to-Jupiter-Family-Comet transitional objects.

Approach: Our campaign involves the long-term dust comae monitoring (via imaging, photometry, and morphology) of 29 Centaurs with known periods of repetitive activity (i. e., Centaurs with cometary designations) and 26 JFCs with perihelia greater than 4.5 au (i. e., just barely closer in than the Centaur region). We have been actively collecting broadband imaging data for this group of targets since 2016 and have compiled serendipitous detections through searches of archival survey data (e. g., DECam), extending our coverage to 2013 for many objects. This group of distantly active primordial small bodies is chosen because their orbits are fully contained in a region too cold for vigorous water-ice-sublimation driven comae, allowing investigations of other less understood mechanisms (e. g., CO vs. CO_2 sublimation, or trapped gases released during the crystallization of amorphous water ice [3, 4]). The secular lightcurves and dust production rates as a function of time and heliocentric distance resulting from our program will provide the largest number and longest baseline of dust comae activity measurements for a statistically significant population of distantly active bodies to date. As the dust production is tightly linked to the volatile drivers of a comet's activity [3, 4], this comprehensive dataset will provide vital constraints for future large-scale thermophysical modeling efforts focused on investigating nuclei volatile compositions. We will present a summary of our monitoring so far and show results from particularly notable objects in the sample.

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NOTES

Observations of Active Centaurs and Distant Comets

Womack, M.[1*]
[1]National Science Foundation and Department of Physics, University of Central Florida, USA, (mariawomack@gmail.com)

Observing Centaurs and comets at the earliest stages of activity before vigorous water-ice sublimation begins can help fill a critical knowledge gap about their gas and dust emissions. Many of these objects exhibit long-term quiescent activity that is punctuated by sporadic outbursts or even fragmentation events. Models of nucleus structure, composition, and activity can be tested by simultaneous measurements of gas and dust comae over a large range of heliocentric distances. Far from the Sun the sublimation and outgassing of hyper-volatiles, such as CO and CO_2, becomes important, as does the amorphous-to-crystalline water-ice transition and mass wasting events, both of which can release trapped volatiles. The measured abundance ratios of CO/CO_2 and other key species constrain models of nucleus activity and icy body formation and evolution. Centaurs, which are in the transition stage between Kuiper Belt objects and Jupiter family comets, are relevant, especially those which are passing through the dynamical Gateway region near Jupiter. We will review many active Centaurs, including 29P/Schwassmann-Wachmann 1, 2060 Chiron, 174P/Echeclus, P/2019 LD2 (ATLAS), and 39P/Oterma. We will also examine what observational constraints are provided from the distant activity of some Jupiter Family Comets, (such as 159P/LONEOS and 103P/Hartley 2), and Oort Cloud comets (such as C/1995 O1 (Hale-Bopp), C/2010 U3 (Boattini), C/2016 R2 (PanSTARRS), C/2017 K2 (PanSTARRS)). Since a very long baseline on heliocentric distance is needed to improve the models, we will also review many valuable contributions from the amateur community for establishing a reliable long-term record of activity and make recommendations for constructing improved lightcurves and partnerships. This material is based in part on work done by M.W. while serving at the U.S. National Science Foundation.

NOTES

Friday 8th

Ejecta Creation and Evolution After the DART Impact

Rivkin, A.S.[1*] for the DART Investigation Team[2]
[1]JHU/APL, USA, [2]Various Around the World

The Double Asteroid Redirection Test (DART) is NASA's first planetary defense test mission. It was designed to test the kinetic impactor technique of asteroid deflection, where the momentum of a colliding spacecraft is used to change the momentum, and thus the orbit, of an asteroid of interest [1]. DART crashed into Dimorphos, the 150-m diameter satellite of (65803) Didymos (which is an S-class asteroid 750 m in diameter), in September 2022 [2], with the aftermath observed by the Light Italian CubeSat for Imaging of Asteroids (LICIACube, [3]) and ground- and space-based telescopes making continued observations [4,5].

While it was recognized that the DART impact into Dimorphos would create some ejecta, the mass of and momentum carried by that ejecta was a matter of debate. Models published by team members prior to DART's arrival considered ejecta masses as high as 6×10^6 kg [6] and momentum transfer enhancement factors of up to 5 [7], but observers needed to prepare for cases where the orbit period change was more modest and difficult to observe, situations associated with little ejecta. It was quickly evident, however, that the real impact created ejecta masses that likely approach or exceed 10^7 kg [8,9].

The material in the ejecta cone created by DART was swept back by solar radiation pressure into a tail within a few days of the impact, and a hypothetical astronomer who was unaware of DART and observed Didymos in October 2022 might think they had discovered a new comet. While the definition of a comet is beyond the scope of this abstract, Didymos' tail has persisted for months after the impact. The DART team continues to monitor its evolution and nature, and has been compiling and presenting its work to the community.

This presentation will discuss the DART mission and synthesize the work done by the international DART Investigation Team to observe, analyze, and model the ejecta trail made by the spacecraft impact. It will also compare the evolution and properties of the trail to what has been seen in naturally-occurring active asteroids [10].

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NOTES

Large particles in active small bodies

Kolokolova, L.[1*], Markkanen, J.[2], Mackowski, D.[3], Ivanova, O.[4], Rosenbush, V.[5]
[1]University of Maryland, USA, (lkolokol@umd.edu), [2]Institut für Geophysik und Extraterrestrische Physik, TU Braunschweig, Germany, [3]Auburn University, AL, USA, [4]Astronomical Institute of the Slovak Academy of Sciences, Slovakia, [5]Main Astronomical Observatory of the National Academy of Sciences of Ukraine, Kyiv, Ukraine

Recent observations of different active objects (comets, active asteroids, DART impact ejecta) show an abundance of dust particles in the size range of hundreds of microns and even millimeters. Evidence of this is in situ data for comets and asteroids; also, they show unusual photometric and polarimetric properties, specifically, their phase curves are very different from those considered typical for cosmic dust. Laboratory measurements of large particles [1] showed that the unusual phase curves can be characteristics of mm-size particles. However, the most popular computational techniques that model light scattering by dust particles (e. g., T-matrix, DDA) are not capable to simulate the photopolarimetric properties of particles of size larger than 10–20 microns as the computations for such particles are too demanding to the computer resources and cannot be handled even with modern supercomputer clusters.

In this presentation, we consider some observations of the active bodies and new techniques recently developed to model light scattering by large particles to overcome computational problems. Specifically, we describe a multi-sphere superposition method for large-scale systems based on an accelerated T-matrix algorithm [2] and its results that allow seeing some regularities in light scattering by large aggregates depending on their material, number, and size of spheres. We will also introduce the Fast superposition T-matrix method (FaSTMM) which uses the fast multipole method (FMM) to speed up the superposition Tmatrix solution [3]. The FMM forms monomer groups hierarchically and computes electromagnetic interactions between the separate groups at each level of the hierarchy. FaSTMM code is available at `https://wiki.helsinki.fi/display/PSR/`. FaSTMM was successfully used to model large dust particles in the coma of comet 67P/Churyumov-Gerasimenko and could successfully reproduce its unusual photometric phase curve[4]. It also successfully reproduces the photometric and polarimetric phase curves observed for the debris disk HR 4796a [5], indicating the presence of active bodies in other planetary systems.

We will present photopolarimetric observations of comet C/2014 B1 (Schwartz) at 9.6 au and show that the FaSTMM simulations of its polarization, color, and their change within the coma require particles of size up to several millimeters.

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NOTES

Detailed modeling of the active asteroid P/2012 F5

Drahus, M.[1*], Waniak, W.[1], and Guzik, P.[1]
[1]Astronomical Observatory of the Jagiellonian University in Cracow, Poland, (drahus@oa.uj.edu.pl)

One of the most remarkable recent advances in solar system science is the direct observation of asteroidal disruptions generating comet-like dust activity (e. g. [1], [2], [3]). While the causes are often not fully understood, various arguments suggest rotational fission resulting from long-term spin-up or a hypervelocity collision with another minor object. P/2012 F5 is a $\sim$2 km diameter [4] main-belt asteroid that revealed itself thanks to a short-lasting ejection of dust in mid 2011 [5]. Our team observed this object with Keck in 2014, which allowed us to discover several small fragments, still cocooned in the dust trail, and measure a short rotation period of 3.24 hr [3]. The rapid spin of P/2012 F5 suggested rotational fission as the cause of the fragmentation [3]. To further understand the system, we secured high-resolution HST imaging data of P/2012 F5 from three consecutive oppositions: 2015/2016, 2017, and 2018. The data revealed over a dozen of small fragments, including new objects ejected between the observations [6]. Importantly, the fragments are long-lived and appear as point sources, showing that P/2012 F5 is actively forming a new full-scale asteroid family – possibly the first known to originate from rotational fission rather than a collision with another object [6]. Thanks to the excellent angular resolution and the long time-span of the HST data, it is possible to accurately reconstruct the fragment ejection times and geometry via detailed dynamical modeling of the system. We will present the results of such modeling, and use these results to conclusively establish the origin of the P/2012 F5 activity. We conclude that strengthless asteroids that are, at the same time, small enough to be susceptible to YORP spin-up, may undergo rotational (but also collisional) activation on a massive scale. The number of such objects will soon dramatically increase thanks to LSST.

This research is based on observations made with the NASA/ESA Hubble Space Telescope obtained from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with programs GO 14192, GO/DD 14475, GO 14798, and GO 15360. M.D. is grateful for support from the National Science Centre (NCN) of Poland through FUGA Fellowship grant 2014/12/S/ST9/00426 and SONATA BIS grant 2016/22/E/ST9/00109. P.G. appreciates support from NCN through ETIUDA Scholarship grant 2020/36/T/ST9/00596. All authors acknowledge support from the Polish Ministry of Science and Higher Education through grant DIR/WK/2018/12.

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NOTES

Dealing with the parent bodies in the Meteor Data Center

Ďurišová, S.[1*], Hajduková, M.[1]
[1]Astronomical Institute of the Slovak Academy of Sciences, Bratislava, Slovakia,
(sdurisova@astro.sk); (astromia@savba.sk)

There are many unknown factors while investigating the activity of comets and active asteroids. The creation of the meteoroid streams is the outcome of their activity and the resulting meteor showers are the way for the terrestrial observers to detect it.

Currently, the only known database containing both meteor shower parameters and the parent bodies associated with their meteoroid streams is the IAU Meteor Data Center (MDC) Shower database (SD). At this moment, there are 929 meteor showers in the SD, including 110 established showers and 28 waiting to be established. The rest belongs to the working list, waiting for their existence to be either confirmed or disproved.

Although the SD does contain information about the parent bodies associated with the showers, only about 16 % of all listed showers have a parent body linked to them. If we look at the established showers only, the percentage is slightly above 15 %. It is important to note that it has not yet been possible to submit a parent body suggestion (for a stream listed in the SD) without also submitting the corresponding shower parameters. The DS also does not offer any other information regarding the method used for associating the parent body with the corresponding stream apart from a flag "?" to mark some dubious relationships.

In the past, it was mainly comets that were associated with meteor showers, but nowadays, asteroid associations are often proposed as well. But many of those suggestions are often proposed only due to the similarity between the mean orbital parameters of the shower and the asteroid orbit [e. g. 1]. Such relationships should be confirmed using a different method, e. g. modeling [2]. Asteroid-shower associations are well accepted in the case of active asteroids such as 3200 Phaethon and the Geminid meteoroid stream [3], but many similar linkages are questionable since there is no proof of the asteroid activity. As seen in the paper done by Guennoun et al. [4], out of 54 promising new parent body candidates, only 3 passed their test to rule out a possible chance association. It is clear, that random associations are not uncommon and should be reinvestigated or, at least, treated with care. The aim of our work is to search as many sources mentioning the possible shower parent bodies as feasible and create a list of possible meteor shower parent bodies, taking into account the method of investigation and looking into the random associations created within the Solar System.

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NOTES

The Asteroids-Comets-TNOs continuum

Fornasier, S.[1,2*]
[1]LESIA, Université Paris Cité, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, 92190 Meudon, France, (sonia.fornasier@obspm.fr), [2]Institut Universitaire de France (IUF), Paris, France

Recent and past studies have shown that there is a continuous trend between the different classes of asteroids and the outer solar system minor bodies. In particular, the strict distinction between asteroids and comets is now being challenged. Inactive objects have been observed on cometary orbits, probably comets that are depleted of their volatiles. Conversely, objects exhibiting cometary activity have been found in the main asteroid belt, including the so called main belt comets, mostly but not exclusively associated with the Themis dynamical family [1, 2]. Water ice has been reported on the surfaces of asteroid (24) Themis as well as (65) Cybele, both from the outer part of the asteroid belt [3], and water vapor and evidences of exposed water ice, beside aqueous altered products and carbonates, found on the dwarf planet Ceres, from Herschel and Dawn missions observations [4,5]. Also the Near Earth Object Bennu shows activity with a number of particles ejected and observed by the OSIRIS-REX mission.

Comets are obviously active, and the Rosetta mission, which followed comet 67P/CG for more than 2 years over one third of its orbit, showed the complexity of the cometary evolution and activity. Water and volatiles, even if they are abundant inside the cometary nuclei, are rarely exposed in form of ice on the nucleus, and, in the case of 67P, water ice occupies only 0.1 % of the total nucleus surface, and it is exposed as tiny bright spots having a typical size smaller than 1 m [6]. Thus, high spatial resolution is mandatory to detect water ice on cometary nuclei and probably, when existing, on dark asteroids. Low amount of dark refractory material may quickly mask water ice signatures on cometary surfaces or other active bodies of the solar system.

TNOs are the sources of short period comets and Centaurs, and several of them shown water ice absorption features, mostly in crystalline form, while methane ice has been detected only in some dwarf planets. 29P/Schwassmann-Wachmann 1 is the only Centaur known to be continuously active and experiencing regular major outbursts. TNOs and Jupiter Family Comets (JFC) are at opposite ends of the evolutionary process, with the Centaur population a less altered, transitional bridge between them. The comparison between Arrokoth and the nucleus of comet 67P, observed by New Horizon and Rosetta missions, respectively, clearly indicates an evolutionary trend from the smoother surfaces of TNOs, which stay in extremely cold environment, and comets, which are eroded and shaped by the cometary activity.

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NOTES

The TRANSient NEOs, the missing link in the asteroids-comets continuum

Ieva, S.[1*], Ishiguro, M.[2], Perna, D.[1], Mazzotta Epifani, E.[1], Dotto, E.[1], Petropoulou, V.[1], Hasselmann, P. H.[1], Deshapriya, P. J. D.[1], Bach, Y. P.[2], Jin, S.[2]
[1]INAF – Osservatorio Astronomico di Roma, Italy (simone.ieva@inaf.it), [2]Seoul National University, Republic of Korea

The classical distinction between asteroids, rocky and inert, and comets, ice-rich and active, has been blended in the last 15 years, with the discovery of transitional bodies: solar system objects showing in essence the dynamical and/or physical characteristics of both classes. Asteroids and comets are now considered as simply end members of an observational, physical, and dynamical continuum. Supporting this theory is the fact that activity detection could actually be dependent on instrumental sensitivity, i. e. many asteroids that are currently considered inactive could in fact be weakly active but have thus far escaped detection [1]. One factor in this growing recognition is a steady improvement in the ability of astronomers to detect weak activity. Activity was detected on (3200) Phaethon [2] and (3552) Don Quixote[3], motivated by the fact that independent sources indicate a potential activity (i. e., Phaethon's association with the Geminid meteor stream and Don Quixote's obviously cometary orbit). For (101955) Bennu, activity was observed serendipitously, being the target of the NASA OSIRIS-REx mission [4]. Identification of active objects is also complicated by the fact that activity is usually a transient phenomenon. Active icy objects can become dormant when their surface volatiles are depleted or buried by a non-volatile crust [5]. At the same time, the distance from the Sun can heavily influence the activity rate, thus resulting in objects observed inactive most of the time, while being active when reaching their perihelion.

For all these reasons in 2022 we started a new project, called "TRANSNEO" and financed by the Italian National Institute for Astrophysics (INAF). We decided to target Near-Earth objects (NEOs) associated with activity that often show both the asteroid/comet designation. Some of these NEOs have been discovered as asteroids but have subsequently shown intense activity (333P/2007 VA85); others were flagged as comets, but exhibit an asteroidal aspect (107P/ 4015 Wilson-Harrington). Some of these frontier bodies have also been identified as progenitors of meteor showers, such as 2009 WN25 for the November i Draconids [6], 169P for the Taurids [7], or (3200) Phaeton for the Geminids [2]. We target transient NEOs because their repeated passages around the Sun make it in principle easier to detect a potential activity; moreover, they can be extremely accessible for observations and a future space mission [8], and activity on NEO surfaces has been recently discovered even on apparently surprising places (see [4]), thus attracting the interest of various space agencies. We will present the latest results of the TRANSNEO project and put it in the larger context of active asteroids in the Solar System.

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NOTES

Close Observations of Outer Solar System Small Bodies

Parker, J. Wm.[1*]
[1]Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO 80302, USA, (joel@boulder.swri.edu)

Visiting small bodies in the solar system with spacecraft brings an obvious advantage of much higher spatial resolution and sensitivity for many aspects of detection and study of activity. In this presentation I look at a few examples from the Rosetta, New Horizons, and Lucy missions and their observations of outer solar system small bodies:

Rosetta orbited Jupiter-family comet 67P/Churyumov-Gerasimenko for two years, studying the comet and its evolution as it passed through perihelion with an array of remote and in-situ instruments. A key result regarding the chemical composition of the coma was the detection of O_2 by the ROSINA mass spectrometer (Bieler et al. 2015) and the Alice UV spectrometer (Keeney et al. 2017), as well as measurements and significant upper limits for other species.

New Horizons flew past Pluto in 2015 and the Kuiper belt object Arrokoth in 2019. An Alice UV spectrometer – sibling to the one on Rosetta – did a search for escaping volatiles from this small body during the encounter at a heliocentric distance of 43 au; no detections were made in the UV, and Alice provided sensitive upper limits (Gladstone et al. 2022).

Lucy will fly past 10 small bodies during its prime mission: two main belt asteroids in 2023–2025, six Jupiter Trojans (4 primaries, 2 satellites) in the L4 swarm in 2027–2028, and a large binary in the L5 swarm in 2033. The mission science team's Activity Working Group has developed several measurement techniques for monitoring activity and searching for coma.

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NOTES

Application of NoiseChisel to detecting faint small-body activity with the LSST

Rożek, A.[1*], Snodgrass, C.[1]
[1]Institute for Astronomy, University of Edinburgh, UK, (a.rozek@ed.ac.uk)

One of the four main science themes of the LSST will be "Taking an inventory of the Solar System", increasing the numbers of known small bodies by at least an order of magnitude [1]. One of the major interests of the LSST Solar System Science Collaboration (SSSC) is a study of small body activity. Comets and asteroids have been traditionally considered separate topics due to their different formation circumstances and dynamical properties. However, we now know objects on typically asteroidal orbits might display signs of activity due to a range of mechanisms including comet-like outgassing, rotationally-induced mass loss, or collisions. Observations with LSST will reveal new examples of so-called main-belt comets and aid activity searches in near-Earth space. At large heliocentric distances LSST will also help understand early onset of cometary activity and likely discover an object that will become the target of upcoming ESA's Comet Interceptor mission. Study of activity requires first an efficient method of activity detection, preferably automated to deal with the volume of LSST data. Manual vetting of all LSST small body observations for activity through visual assessment will be impractical. The SSSC is preparing to maximise the science output from the LSST [2] and one of the tasks is development of activity detection tools. Majority of the coma detection methods rely on comparison between the comets' photometric profile and field stars: elongation, or contribution from coma of a specific, assumed profile. Another possibility is a tail detection by measuring brightness in radial segments of sky around the object, searching for excess brightness [3]. We will present initial results on the study of feasibility of NoiseChisel for activity detection [4,5]. The tool is developed as part of the GNU Astro suite to investigate low-surface-brightness extended sources and can be adopted for cometary activity detection. The method is independent from image properties such as photometric stellar profiles, but rather relies on noise statistics, carving out signal from sky background. In case of activity detection, it provides means for finding coma or tail without predefining their shapes. This approach was not used in small body science before and would be very useful especially in detecting weak activity, asymmetric features, and irregular activity which is often the case for main-belt comets. We will present a comparison of the effectiveness of this novel method and other activity detection techniques, for implementation on LSST-scale datasets.

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NOTES

List of posters

All-time Session

Formation of Organic Species in the Gas Phase Cometary Coma

Ahmed, S.[1*], Acharyya, K.[2]
[1]Physical Research Laboratory, India, (ahmed.sana92@gmail.com), [2]Physical Research Laboratory, India

Comets are the relics of the protoplanetary disk that formed the Solar System and are made up of volatile ices, which have been largely unprocessed since their incorporation in the cometary interiors. Comets are likely to have delivered volatile organics and prebiotic material to the planet by impact processes [1,2]. Organics are the seeds for creating molecules of biological interest, and investigations of their formation in comets can give clues towards understanding the prebiotic chemistry. Many volatile species have been detected in comets from remote and in situ measurements. At present, the total number of volatile species identified in comets, including tentative detections, stands at 72, out of which 37 are complex organic molecules [3]. It has not yet been proven that all of the molecules observed in the coma of comets originate from the ices inside the cometary nucleus. Thus, it is pertinent to study the coma chemistry, with emphasis on the gas-phase formation pathways and how successful they are in producing organics in a cometary coma.

We selected a sample of four comets for our study: C/1996 B2 (Hyakutake), C/2012 F6 (Lemmon), C/2013 R1 (Lovejoy) and C/2014 Q2 (Lovejoy). All of these are bright comets, with high production rates near perihelion, which facilitated the remote detection of many organic molecules, while sensitive upper limits were obtained for some other organics. The coma of these comets is modelled by using a combined chemical-hydrodynamical multi-fluid model that is based on the fluid conservation equations of number density, mass, momentum, and energy. The model also uses a large chemical network to define an active gas phase coma chemistry that includes photochemical reactions, bimolecular ion-neutral and neutral-neutral reactions, recombination reactions and electron impact reactions. The multi-fluid approach is to divide the neutral species, ions and electrons into three separate fluids, and energy exchange between the fluids is included. Our model results show that by incorporating gas phase formation pathways, the production rates for several complex organic molecules can be increased, which can account at least partially towards the total coma abundance of these species. We also found that factors such as initial volatile abundance, relative abundances of the reactants and temperature of the reacting species significantly affect the formation rates of molecular species in different regions of the coma.

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NOTES

May a comet dynamically capture and keep meteoroids in its vicinity?

Borderes-Motta, G.[1*], Kastinen, D.[1], Moraes, R.A.[2], Kero, J.[1], Winter, O.C.[3]
[1]Swedish Institute of Space Physic (IRF), Sweden, (gabriel.borderes.motta@irf.se), [2]Federal Institute of Education, Science and Technology (IFSP), Brazil, [3]São Paulo State University (UNESP), Brazil

In 2023 the trans-Neptunian object Quaoar became a member of a growing group of non-ice-giant space objects with rings [1]. The presence of rings around small bodies from the outer solar system give rise to new questions. Can a small body support a dynamic structure of meteoroids in the inner solar system despite the solar radiation pressure?

To answer this question, we go one step further on the work of Borderes-Motta et al. [2]. In that work, the authors identified periodic and quasi-periodic orbits around stable equilibrium points of the comet 9P/Tempel via the Poincaré Surface of Section.

We now populate the stable regions predicted with particles and simulate the orbital dynamics. For this simulation, we used the package N-BoM [3]. This package uses the MASCONS model to compute the gravitational potential of irregular bodies and integrates the n-body problem, including t solar radiation pressure. At the end of the simulations, we can estimate if, and how long, the particles can remain stable in Tempel's orbit.

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NOTES

No evidence for interstellar meteors in the CNEOS database

Hajduková, M.[1*], Sterken, V.[2], Stober, G.[3], Barghini, D.[4,5], Vaubaillon, J.[6], Ďurišová, S.[1], and Koten, P.[7]
[1]Astronomical Institute, Slovak Academy of Sciences, Bratislava, Slovakia, [2]Institute for Particle Physics and Astrophysics, ETH, Zürich, Switzerland, [3]Institute of Applied Physics & Oeschger Center for Climate Change Research, Microwave Physics, University of Bern, Switzerland, [4]Istituto Nazionale di Astrofisica, Osservatorio Astrofisico di Torino, Italy, [5]Università degli Studi di Torino – Dipartimento di Fisica, Torino, Italy, [6]Observatoire de Paris, I.M.C.C.E., Paris, France, [7]Astronomical Institute of the Czech Academy of Sciences, Ondřejov, Czech Republic

We present a study in which we examine the probability of two fireballs, observed on January 8, 2014, and March 9, 2017, as recorded in the CNEOS (Center for Near Earth Objects Studies) catalog, being of interstellar origin. We provide arguments for and against such an origin, and outline the necessary criteria for an unambiguous identification of an interstellar meteor. Both meteoroids exhibited seemingly unusual behavior in the atmosphere, considering their incompatible parameters provided in the catalog (these do not contain uncertainties). As a result, they displayed a hyperbolic velocity relative to the Sun.

We thoroughly analyzed each vector component of the velocity for all events in the CNEOS catalog and determined statistical measurement errors in velocities given in the catalog. We simulated the velocity uncertainties and evaluated if each event in the database becomes compatible with a closed orbit at a 3-sigma confidence. We also estimated uncertainties in the radiant position by a simple simulation, taking into account the most probable image resolution used for the trajectory determination of the CNEOS meteors. The potential errors we obtained in both speed and radiant are too large to reliably consider both events as candidates for interstellar fireballs.

We conclude that the possible interstellar origin of the two CNEOS meteors cannot be confirmed on the basis of the accessible data for them. Applying Occam's razor, the simplest explanation for the contradictions in their parameters is that the velocity of the meteoroid was overestimated, considering the significant velocity uncertainty (both in direction and modulus) compatible with the estimated CNEOS data error bars. Moreover, based on exoplanetary research, there is no reason to anticipate the presence of exotic materials from interstellar meteoroids. Therefore, unusual atmospheric behavior from such meteoroids in not expected. Our analysis validates the widely acknowledged viewpoint that the data are likely incorrect, rather than questioning the established theories and models that have been applied on these two meteor events so far.

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NOTES

Photometric investigation of (493) Griseldis and (6478) Gault in their last apparitions

Husárik, M.[1*], Ivanova, O.I.[1,2,3]
[1]Astronomical Institute of the Slovak Academy of Sciences, SK-05960 Tatranská Lomnica, Slovakia, (mhusarik@ta3.sk), [2]Main Astronomical Observatory of the National Academy of Sciences of Ukraine, 03143, Kyiv, 27 Zabolotnoho Str., Ukraine, [3]Taras Shevchenko National University of Kyiv, Astronomical Observatory, 04053, Kyiv, 3 Observatorna Str., Ukraine

In this presentation, we show some photometric results for two candidates known as active asteroids. We have been studying and observing this type of interesting solar system objects at the Skalnaté Pleso Observatory for a long time interval.

The first object is (493) Griseldis. It was observed to have an activity or a broad tail in March 2015. Archival images as well as new observations have shown that the asteroid shows no activity. The aim of our observations in 2019 and 2020 was to spot possible activity, but also to determine the rotation period, the amplitude of the changes, or to try to define the coordinates of the axis of rotation.

The second object is the well-known (6478) Gault, for which activity has been observed in multiple apparitions. No activity has been shown in 2020 and also now, in 2023. Observations of Gault are ongoing in 2023, but it appears that the effective diameter and absolute magnitude are slightly different from the values in 2020.

The observations of both active asteroids were carried out with the 0.61-m $f/4.3$ Newton reflector at the Skalnaté Pleso Observatory (Slovakia, IAU code 056) and CCD camera SBIG ST-10XME and with the 1.3-m $f/8.1$ Cassegrain-Nasmyth reflector at the same observatory and CCD camera FLI Proline 230. We obtained photometric data using broad-band Johnson-Cousins B, V, and R filters.

NOTES

Microphysics of dust in distant comets

Ivanova, O.V.[1,2,3], Luk'yanyk, I.[3], Markkanen, J.[4,5], Kolokolova, L.[6], Rosenbush, V.[3]
[1]Astronomical Institute of the Slovak Academy of Sciences, 05960 Tatranská Lomnica, Slovak Republic, [2]Main Astronomical Observatory of the National Academy of Sciences, 03143 Kyiv, Ukraine, [3]Astronomical Observatory of Taras Shevchenko National University of Kyiv, 04053 Kyiv, Ukraine, [4]Institut für Geophysik und Extraterrestrische Physik, TU Braunschweig, 38092 Germany, [5]Max Planck Institute for Solar System Research, 37077 Germany, [6]University of Maryland, College Park, Maryland, USA

Modern conceptions of the Solar System identify several reservoirs of small bodies, including the Edgeworth-Kuiper Belt, the Scattered Disk, the Oort Cloud, and the Main Asteroid Belt. Dynamic studies indicate that the Oort Cloud is the primary source of "almost isotropic comets", such as long-period and Halley-type comets. In contrast, ecliptic and Encke-type comets are believed to have originated mainly from the Edgeworth-Kuiper Belt. The Scattered Disk is associated with Jupiter family comets and centaurs. The distribution of comets across these reservoirs suggests that their physical and chemical properties may vary due to formation in different locations and subsequent evolutionary changes within different dynamic groups. Investigating the physical and chemical properties of small bodies can shed light on the origin and evolution of the Solar System as a whole. Since 2011, we have provided a comprehensive program of investigations on distant comets using various observation methods, including photometric, polarimetric, spectropolarimetric, and spectroscopic observations. These observations were carried out using 18 telescopes of different sizes, with a particular focus on the 6-meter BTA telescope (SAO) [1–6]. Our program has yielded significant findings, including: Detailed maps of the polarization parameters for distant comets, revealing higher values of linear polarization degree compared to comets closer to the Sun at equivalent phase angles. Computer modeling demonstrates compositional differences between particles in distant comets and those observed in short-period comets. Dynamic simulations indicate that flare activity in comets may be caused by meteoroid impacts on comet nuclei. Modeling studies show that highly porous aggregates composed of ice and red materials (e. g., organics, silicates) can reproduce polarimetric and color characteristics observed near comet nuclei. The observed variability in comet coma characteristics suggests significant and variable activity within the nucleus, possibly with multiple active areas releasing substances with varying ratios of water ice, CO_2 ice, and refractory dust. These results enhance our understanding of distant comets and contribute to the broader knowledge of the Solar System's formation and evolution.

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Quasi-simultaneous photometric, polarimetric, and spectral observations of comet 108P/Ciffreo

Kulish, K.V.[1*], Ivanova, O.V.[2,3,4], Luk'yanyk, I.V.[3]
[1]Division of Astronomy and Astrophysics, Faculty of Mathematics, Physics and Informatics, Comenius University, 842 48 Bratislava, Slovakia, [2]Astronomical Institute of the Slovak Academy of Sciences, Tatranská Lomnica, 059 60 Vysoké Tatry, Slovakia, [3]Astronomical Observatory of Taras Shevchenko National University of Kyiv, 3 Observatorna St., 04053 Kyiv, Ukraine, [4]Main Astronomical Observatory of the National Academy of Sciences, 27 Akademika Zabolotnoho St., 03143 Kyiv, Ukraine

The Jupiter family of comets stands out among the short-period comets. The short orbital periods of these comets allow us to observe the evolutionary changes of these bodies in a reasonably short time. About 400 such comets are already known, and space missions have been carried out to several of them. We present the results of photometric, long-slit spectrometric, and polarimetric observations of comet 108P/Ciffreo. Observations were made on November 28, 2014, after the perihelion passage of the comet using the 6-m telescope BTA SAO. We identified the gas emissions from the C_2, C_3, and NH_2 molecules within the range $\lambda 3750 - 7100$ Å. The comet's activity is characterized by the dust production $Af\rho$ of 69 ± 2 cm. To reveal the inner structure of the coma and its low-contrast features, we treated the original images with digital filters. The blob [1] structure and tail were detected in the coma. We observed spatial variations in color and polarization over the coma and active structures.

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NOTES

Physical properties of extrasolar comets based on simulation of asymmetric dimming events in the TESS and Kepler database

Luk'yanyk, I.[1*], Vasylenko, M.[2], Dobrycheva, D.[2], Kulyk, I.[1,2], Pavlenko, Y.[2], Shubina, O.[2,3]
[1]Taras Shevchenko National University of Kyiv, Ukraine, [2]The Main astronomical observatory of the National academy of sciences of Ukraine, Kyiv, Ukraine, [3]Astronomical Institute of the Slovak Academy of Sciences, Slovakia

Theories of planetary system formation in modern astrophysics predict the presence of a substantial population of planetesimals and dust within debris disks. These disks have been observed around numerous main sequence stars, revealing complex structures that are likely associated with perturbations caused by hidden planets [1,2,3]. It has been demonstrated that gravitational interactions between planets and planetesimals, particularly through the mean-motion resonance mechanism, can trigger the influx of star-grazing bodies [4]. Such events have been observed spectroscopically as falling evaporating bodies and photometrically as asymmetric dimming events in photometric time series [5]. Asymmetric profiles indicating a decrease in star brightness have been identified in the photometric time series from the TESS and Kepler databases [6 and references therein]. To simulate these events, a simple 1-D model of a cometary tail has been employed, providing estimates for the orbital and physical properties of the transiting comets [see, e. g. 7].

In this study, we present preliminary results on the retrieval of photometric shapes for known exocomet transits, utilizing a Monte-Carlo approach to model the distribution of dust particles within cometary tails. This approach allows us to refine estimations of several physical parameters, including the size of particles comprising the dust coma surrounding the exocomet, the distribution of particle sizes, the timespan for comet tail formation, and the dust production of the cometary nucleus.

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NOTES

Study of comets C/2020 V2 and C/2022 E3 through narrowband filters

Shubina, O.[1,2*], Ivanova, O.[1,2,3], Husárik, M.[1], Luk'yanyk, I.[3], Safonova M.[4], Venkataramana A. K.[5], Selvakumar G.[5], Narang M.[6]

[1]Astronomical Institute of Slovak academy of sciences, Slovak Republic, (oshubina@ta3.sk), [2]Main astronomical observatory of National academy of sciences of Ukraine, Ukraine, [3]Astronomical observatory of Taras Shevchenko national university of Kyiv, Ukraine, [4]Indian Institute of Astrophysics, Bengaluru, India, [5]Indian Institute of Astrophysics, Vainu Bappu Observatory, Kavalur, India, [6]Institute of Astronomy and Astrophysics, Academia Sinica, Taipei, Taiwan

We present the results of photometric observations of two hyperbolic comets C/2020 V2 and C/2022 E3 (ZTF) in February 2023 obtained within narrow-band filters at the 61-cm telescope of Skalnaté Pleso observatory. The intensity distribution over the cometary coma was analyzed. Parameters of dust productivity and colour value $BC - RC$ were calculated. We also estimated the gas production rate of C2 molecules and their distribution over the coma of each comet. In addition to our photometrical study, the spectral investigation was considered. It revealed the emission features of several molecules. The most significant are CN, C_2, C_3, NH_2. We computed the gas production rates of these molecules.

NOTES

Observations of the near-Earth asteroid (4660) Nereus

Troianskyi, V.[1,2,3*], Godunova, V.[4], Serebryanskiy, A.[5], Ivanova, O.[6,7,8], Franco, L.[9], Marchini, A.[10], Bacci, P.[11], Maestripieri, M.[11], Berezin, D.[4], Maigurova, N.[12], Panko, E.[2], and Taradii, V.[4]

[1]Astronomical Observatory of Odesa I. I. Mechnykov National University, Marazlievskaya 1v, 65014 Odesa, Ukraine, (v.troianskyi@onu.edu.ua), [2]Department of Physics and Astronomy FMPIT of Odesa I. I. Mechnykov National University, Pastera Street 42, 65082 Odesa, Ukraine, [3]Astronomical Observatory Institute, Faculty of Physics, Adam Mickiewicz University, Sloneczna 36, 60-286 Poznan, Poland, [4]ICAMER Observatory of NASU, 27 Acad. Zabolotnoho str., 03143 Kyiv, Ukraine, [5]Fesenkov Astrophysical Institute, Observatory 23, 050020 Almaty, Kazakhstan, [6]Astronomical Institute of the Slovak Academy of Sciences, SK-05960 Tatranská Lomnica, Slovak Republic, [7]Main Astronomical Observatory of National Academy of Sciences, 27 Acad. Zabolotnoho str., 03143 Kyiv, Ukraine, [8]Astronomical Observatory, Taras Shevchenko National University of Kyiv, 3 Observatorna str., 04053 Kyiv, Ukraine, [9]Balzaretto Observatory, Rome, Italy, [10]Astronomical Observatory, DSFTA – University of Siena, Via Roma 56, 53100 Siena, Italy, [11]GAMP – San Marcello Pistoiese, Pistoia, Italy, [12]Research Institute "Mykolaiv Astronomical Observatory", 54030 Mykolaiv, Ukraine

On February 28, 1982, E.F. Helin discovered asteroid 1982 DB, also known as (4660) Nereus, at Palomar Observatory, just over a month after its close encounter with Earth on January 23, 1982, at a distance of 0.028 au [1]. The Minor Planet Center (MPC) classified it as a potentially hazardous asteroid, as initial observations of this Apollo-type object indicated its orbit often approaches Earth. Over the years, numerous researchers have analyzed the orbital evolution of (4660) Nereus and concluded that its mutual orbital arrangement offers opportunities for space rendezvous missions [2, 3].

We observed it photometrically from 14 November 2021, when it was visible at $V = 15.2$ mag, until 16 February 2022 ($V = 17.6$ mag), and spectroscopically on 10 December 2021 ($V = 13.0$ mag). This made it an excellent target for observations and determination the physical characterisation.

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NOTES

Comet 29P/Schwassmann-Wachmann 1 during its activity outburst in 2020

Voitko, A.[1*], Ryzhko, Ya.[2], Ivanova, O.[1,3,4], Husárik, M.[1]
[1]Astronomical Institute of the Slovak Academy of Sciences, Tatranská Lomnica, Slovak Republic (avoitko@ta3.sk), [2]Anatoliy Lygun Scientifical Lyceum, Kamianske, Ukraine, [3]Main Astronomical Observatory of National Academy of Sciences, Kyiv, Ukraine, [4]Astronomical Observatory, Taras Shevchenko National University of Kyiv, Kyiv, Ukraine

Our research is aimed at studying the properties of cometary dust through variations of its color. The activity of distant comets at heliocentric distances larger than 3 au has different nature. So far from the Sun activity of comets is driven by sublimation of more volatile species than water or crystallization of water ice (Meech, et al., 2004; Guilbert-Lepoutre, et al., 2015). Moreover, cometary spectra in visible part are mostly free of gaseous emissions at such distances (Ivanova, et al., 2015; Kulyk, et al., 2018).

Comet 29P/Schwassmann-Wachmann 1 is famous for its activity outbursts and continuous activity beyond Jupiter's orbit (Jewitt, 1990). Also, this comet was the first one for which dust color variations were reported (Hartmann, et al., 1982). During the previous study of the comet, it was obtained that activity outburst provoked a change in the chemical composition of dust particles from mostly Fe-Mg silicate and organic to mostly water-ice and Mg-rich (Voitko, et al., 2022).

Here we present results obtained from photometric observations of 29P/Schwassmann-Wachmann 1 taken using the 0.61-m Newtonian telescope of Skalnaté Pleso Observatory (AI SAS) on November 18–26, 2020. These data were much denser than it was in work of Voitko, et al. (2022). The comet possessed the outburst of middle strength, i.e., the change in the magnitude was about 2.5 mag. We have also obtained absolute magnitude, photometric dust color, and the $Af\rho$ parameter as the measure of dust productivity. We have found the blue V-R color of the comet during the outburst maximum. We have also analyzed the coma morphology. During the outburst on November 21, two jets were formed, later it was visible how they evolved and widened.

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