INFRARED MAPPER (IRMA) FOR SUPPORT OF COMET SAMPLE RETURN MISSIONS,

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Introduction: Comets are remnants from the formation of the Solar System, and contain the most pristine material available today for deciphering the physical and chemical conditions of this process. As such, they are very interesting candidates for sample return missions, as indicated for example by the recent mission proposals CAESAR, CONDOR, and CORSAIR to the NASA New Frontiers 4 call. For maximizing the science return from such a mission the optimum selection of sampling site(s) is crucial. To support this selection we propose a remote sensing instrument working in the thermal infrared (TIR) wavelength range.

Science Requirements: Comets are composed of a mixture of ices, dust, and organics, but their surfaces are strongly affected by thermal processes. Subsurface samples from ice-bearing regions could provide the most primitive material available in the Solar System [1] and and would thus be the ideal targets of (ideally cryogenic [2]) sample return missions. Remote sensing instrumentation capable of detecting such icy regions with significant content in organics is therefore highly desirable for the selection of sampling sites with highest scientific interest. For this task, a TIR instrument is an excellent choice because it can detect (sublimating) ice not only on the surface but also in the shallow subsurface with high spatial resolution. Note that even ice on the surface could be masked and non-detectable with spectroscopic methods when intimately mixed with dust or organics [6], but the reduction in temperature caused by sublimation would be easily detectable in the thermal infrared emission. According to [3], the depth of the H_2O sublimation front lies typically in a range of a few mm to 2 cm over the largest part of the orbit. Figure 1 shows the difference in surface temperature between a dry surface and a surface with hidden ice below at a depth of 1 cm as function of heliocentric distance and thermal conductivity (assuming a Jupiter Family [JF] comet on CG-67 orbit with zero obliquity). It can be seen that for a wide range of thermal conductivities a significant reduction in surface temperature between 4 –70 K results, which can be safely detected by a TIR mapper.

Other physical parameters that can be extracted from TIR observations are the thermal inertia and the surface roughness which are correlated to structural and mechanical properties (e.g. porosity and strength, [7]) of the cometary material, and, therefore also provide valuable information for the choice of sampling sites and their context.

In addition to the prime goal of aiding in sample site selection, TIR observations can also provide additional highly valuable scientific information for comet missions. Various organic phases, ices, and minerals show characteristic features in the thermal infrared. TIR spectra of both organics and silicates show many relatively broad features over the wavelength range of 5-20 µm [8]. For this reason spectrally resolved observations of the comet surface in this wavelength region can provide valuable information about mineralogical composition and the organic inventory. Moreover, by observing the outflowing dust in the thermal infrared and simultaneous visible observations the dust albedo could be determined, and the estimation of the total dust mass production could be considerably improved.

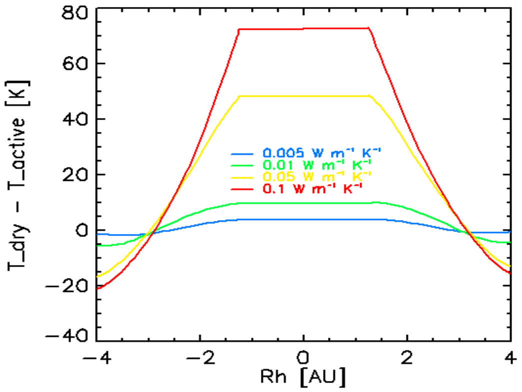

Figure 1 *Surface temperature difference between a dry subsurface and a wet subsurface with hidden ice at a depth of 1cm for a comet on an orbit like 67P as function of heliocentric distance and thermal conductivity at the equator and local noon.*

Scientific instrument requirements: The expected comet surface temperatures for a typical JF comet vary between about 80 K and 400 K, but activity is mostly restricted to the dayside, giving a range in temperature of ~190-400 K. This is the minimum requirement for a TIR instrument dedicated to detect icy regions on a comet. If, in addition, a good estimate of thermal inertia is desired, measurements of the un-illuminated part of the comet are mandatory, thereby lowering the requirement on the minimum temperature to less than 150 K. The noise equivalent temperature difference (NETD) should be lower than 1 K at the minimum temperature of the measurement range, in order to provide sufficient radiometric resolution to distinguish between active and inactive parts of the surface.

The requirements on the temperature described above mainly determine the wavelength range that the instrument needs to cover. Note that the maxima of the Planck function vary between 7.3 µm at 400 K and 19 µm at 150 K. Furthermore, one needs to take into account that organic features in the spectrum are found for wavelengths > 6 µm, a wavelength region which is also very useful for surface roughness investigations. From these considerations it follows that the instrument should cover a wavelength range of 5 to larger than 20µm.

The required spatial resolution depends on the typical size of ice-rich areas on or below the surface of the comet. Results of the Rosetta mission indicate that icy patches have typical extents of a few m to a few tens of meters ([4], [5]). Assuming that the accuracy of the sampling is in the range of a few m the requirements on spatial resolution could be formulated as ~10-20 m on a global scale and ~1 m for the characterization of possible sampling sites.

The required resolution to fully resolve the broad features of organics and silicates is about $\lambda/\Delta\lambda$ =50-100. Ootsubo et al. [9] detected organic signatures on the nucleus of a dead comet by telescopic observation with an effective resolution of $\lambda/\Delta\lambda$ =35. For the identification of silicates the wavelength region of the Christiansen feature between 7 µm and 9 µm is very important. Other diagnostic spectral features of silicates, like the Reststrahlen bands and transparency features lie in the 9 - 14 µm spectral region.

Instrument concept: The instrument concept (Infrared Mapper, or IRMA)is based on heritage from the MERTIS instrument on BepiColombo and TMAP, a proposal for the IVO discovery mission. An uncooled microbolometer is chosen as the detector. This choice is motivated by keeping the resources (energy, mass) low while providing sufficient performance to fulfill the measurement task. Because of the low ground sampling velocities for an orbiting spacecraft observing a comet, a staring design is chosen. The baseline detector is the 1024×768 pixel Lynred Pico1024 detector with a pixel size of 17 µm. The main optical instrument parameters are a focal length of 135 mm, and an f-number of f/2.5. The resulting FOV is 7.4°, which means that for an assumed global mapping orbit at 50 km distance the ground sampling distance would be 6.3 m, and a typical JF comet would completely fit into the FOV.The baseline optics is a diffraction limited three mirror anastigmate design. According to the Rayleigh resolution criterion the resulting spatial resolution would be 12.6 m at 50 km for wavelengths < 14 µm. For close flybys (R_N < 5 km) aimed at detailed investigations of candidate sampling sites the achievable spatial resolution would thus be of the order of a few dm. The estimated noise equivalent temperature difference as a function of target temperature is given in Fig.2. Already the default wavelength range of 6 to 16 µm of the foreseen detector gives good performance down to temperatures of 160 K if 2×2 pixel binning is employed, but an extension to longer wavelengths could considerably improve the performance and thereby the estimate of the thermal inertia.

Two options are currently considered for the spectral capability of the instrument, a traditional filter wheel design, and a design based on Fabry-Perot MEMS. The second option would be implemented using a dichroic beam splitter together with a second detector. S/N estimates for well-resolved spectra ($\lambda/\Delta\lambda$ >50) show that these observations would require pixel binning, and furthermore are restricted to surface temperatures > 300 K (i.e., heliocentric distances < 1.5 AU).

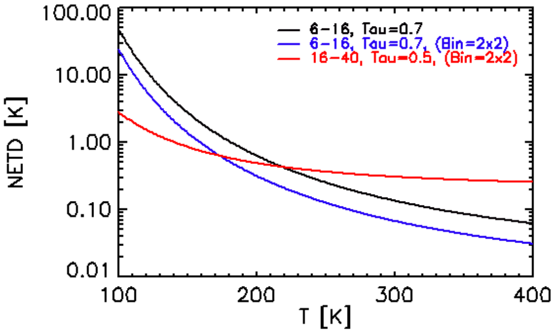

Figure 2 *Noise equivalent temperature difference of IRMA as funcition of surface temperature for 2 broadband filters and with and without pixel binning* .

Summary and Conclusions: Hidden cometary ice can be detected with IRMA by measuring the surface temperature that is reduced by sublimation processes. This works best when the ice is on the surface or shortly below it (cm-range) and when near perihelion. The strength of the temperature reduction depends on the heat conductivity of the upper layer. By deriving the thermal inertia, preferably from temperature measurements at night, clue to the strength of the surface layer can be found. Furthermore, some insight to the surface composition can be gained by the spectral capabilities of the instrument.

References: [1] NASA Decadal Survey 2013-2022. [2] Davidsson, B.J.R., et al. (2020). [3] Davidsson, B.J.R. et al., *MNRAS* (2021) [4] Barucci, M.A., et al., *AA 595 A102* (2016) [5] Oklay, N., et al., *MNRAS 469, 582-597*, (2017) [6] Yoldi, Z., et al., *GRL 42., 6205-6212 (2015).* [7] Grott, M., et al., *Nature Astron. (2019).*[8] Cataldo, C., et al., *MNRAS 429,3025-3039 (2013).* [9] Ootsubo, et al., *Icarus 363 (2021)*