MINUTES
THERMAL EMISSION MEETING #3
Second Meeting at ISSI, Bern, May 2-4, 2012

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Contents

1 Participants and Background

In alphabetic order and with initials to be used throughout the Minutes,

1. BD: Davidsson, Björn (Uppsala University, Sweden)
2. JH: Helbert, Jörn (DLR, Berlin, Germany)
3. EK: Kührt, Ekkehard (DLR, Berlin, Germany)
4. TM: Mueller, Thomas (Max–Planck–Institut für extraterrestrische Physik, Garching, Germany)
5. HR: Rickman, Hans (Uppsala University, Sweden / PAN Space Research Center, Warsaw, Poland)
6. MW: Wilska, Magdalena (PAN Space Research Center, Warsaw, Poland)

The project *Deriving Physical Parameters of Atmosphereless Bodies in the Solar System by Modelling their Thermal Emission* was approved by ISSI in 2010. The previous Team meetings may be summarized as follows.

• November 9–11, 2010 at DLR in Berlin, Germany: Preparation for writing the finally approved proposal.

• October 26–28, 2011 at ISSI in Bern, Switzerland: Defining a number of modelling projects in detail.

The current meeting was held at ISSI in Bern, Switzerland on May 2–4, 2012, organized and chaired by Björn Davidsson and Hans Rickman. The purpose of the meeting was to summarize current activities of the participants (Day I); make detailed planning of Laboratory Projects and deliver progress reports on our Modelling Projects (Day II); discuss the Theme of Block II (focusing on a shared dataset from LRO Diviner provided by Joshua Bandfield) and initiate the planning of publications (Day III).

2 Day I

HR, BD: Welcome words, summary of Agenda.

HR: We should start thinking of the papers we will produce.

TM: What format is ISSI expecting? A particular journal or book?

HR: Any journal, it is up to us.

BD: We may want to use different journals for the papers on modelling, laboratory work and analysis of spacecraft data.

2.1 Talk: Helbert

Jörn Helbert then gave the talk *Planetary Emissivity Laboratory (PEL)*. Since all presentations from the meeting are collected at the Team website
www.mpe.mpg.de/∼tmueller/issi/issi_team.html
the talk is not summarized here. However, the following discussion was made during the talk.

JH: Spectral features of regoliths are dominated by the small grains (size similar to the wavelength). Such small grains seem to be missing on Itokawa.

TM: Isn't this the case for all bodies?

JH: Not for Mercury.

TM: Are spectral features more sensitive to grain size or mineralogy?

JH: Both, why it is important to perform measurements that allow us to disentangle effects of mineralogy and grain size.

TM: Would it be possible to identify wavelength ranges where disentanglement can be done easier than elsewhere?

JH: Christiansen features are only visible when small grains are present.

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BD: Sub–mm observations of some asteroids, like Vesta, yield very low emissivity. Steve Keihm at JPL claims this is due to the usage of thermphysical models which only considers surface temperatures when calculating synthetic spectra. According to him, problems start when object become transparent, and the instrument sees a whole surface slab with a strong temperature gradient. Is there a break–down of Kirchhoffs law at large wavelengths seen in laboratory experiments?

JH: Yes, this has been seen.

BD: This could be topic if study for us.

All: We had a discussion on the physical mechanism that would make a slab emit *less* sub–mm radiation than the very surface itself, which is needed to increase current emissivity estimates. No conclusion was reached, except to check with Keihm on how it works[1].

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JH: The Christiansen feature changes position with temperature due to size changes of the crystals.

[1]Note added by Thomas Müller: In the ACM conference there was a talk given by Hofstadter (http://www.lpi.usra.edu/meetings/acm2012/pdf/6417.pdf). They claim that there is no emissivity issue at long wavelength (submm/mm/cm range). The reasons is that we see layers below the surface where the density is significantly higher, the temperature is lower and therefore the thermal inertia is very different and could explain the observed low fluxes without touching the emissivity. I am not sure I would agree with their findings, but apparently they can explain the Lutetia case very well.

BD: Can impact shocks be distinguished by looking at the Christiansen feature?

JH: Yes, some measurements of this has been done.

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JH: Strong temperature gradients near surfaces of laboratory samples have a strong effect on the measured spectra. We therefore work hard to find ways to eliminate gradients and consider isothermal media.

BD: Why is it desirable to get rid of gradients? Would it not be better to try to reproduce planetary gradients, which certainly are present?

JH: It is very difficult to set a realistic temperature gradient. The gradients are highly dependent on e.g., compaction of the material as function of depth. The strong increase in porosity when approaching the surface of a regolith–covered low–gravity body from below, cannot be reproduced accurately in the laboratory. It is therefore far better to perform the measurement at zero gradient, and then use such results as input to theoretical models which calculate temperature gradients under various conditions.

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JH: The spectral properties of minerals change substantially when they are heated to high temperatures. These effects remain after cooling. For example, sulphur–rich substances which appear bright yellow before heating turn dark after heating.

BD: What is the physical reason?

JH: We do not believe these color changes are due to oxidation or trace gas removal – such processes would certainly have the observed effect but we have made sure the laboratory environment is essentially oxygen–free, and we measure outgassing. Instead, *color centers* is the favored explanation (defects in the crystal structure occurring during extreme heating or irradiation). It is partly reversible, which could also explain why the most extreme spectral alterations tend to disappear over time.

BD: Is this contributing to the general space weathering?

JH: Space weathering is primarily due to formation of nano–phase iron in minerals, but iron is rare in Hermian regolith.

2.2 Talk: Müller

Thomas Müller then gave a talk on *Thermophysical Modelling of Small Bodies*. Since the presentation is available on the website, we here only summarize the discussion during the presentation.

BD: How come ISO only observed 50 asteroids whereas the much shorter IRAS mission covered 2200 objects?

TM: This is the difference between a survey mission (IRAS) and an observatory facility that only observe specific targets (ISO).

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TM: It is usually very difficult to separate thermal inertia and roughness (here discussing disk–integrated photometry), but observations made before and after opposition makes it possible to fix the thermal inertia, since photometric changes versus phase angle is very insensitive to roughness (except for very small phase angles). In order to distinguish a very smooth surface from rough one, it is necessary to have access to observations at short $< 10\,\mu$m wavelengths and/or observations taken at very small phase angles. At 10–100 μm, models with very different roughness are virtually identical.

All: It is an important topic for a paper, and indeed, an important outcome of our entire Team effort, to provide practical and well motivated recommendations for observers on how to disentangle roughness and thermal inertia. This may be particularly important for the observational campaign of asteroid *Apophis* during its Earth encounter in January 2013.

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EK: Only roughness on size–scales larger than the thermal skin depth is observable, as everything smaller than that will be isothermal.

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TM: Eris has a known size from occultations. Even advanced thermophysical models fail to fit the data (which are reliable): if the 100 and 160 μm data are reproduced, the 70 μm data point (which has been measured several times) has an intensity excess of $\sim 50\%$ compared to models. One way to account for this is to introduce a very dark spot that is substantially hotter than the rest of the surface (yielding excess at relatively short wavelengths). Also Makemake suffers similar problems.

EK: Is multiple reflection included in craters and other concave surface features? If the surface has a high albedo, single–scattering approximations will not suffice, and may explain the results.

HR: Is it possible that Eris is surrounded by a cloud of grains, which are small enough to give flux contribution at 70 micron but not at larger wavelengths?

BD: Could the SED be caused by a transparent icy surface layer and temperature gradient effects?

EK: I.e., the solid-state greenhouse effect?

TM: It could be that there are dark hot spots or a cloud of dust grains that could explain observations. Solid state green house effects and transparency should be looked into.

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EK: Models using beaming factors are very problematic as they seek to compensate for several physically very different processes (thermal inertia, roughness) with a single parameter. It may work as a fudge factor for observations at single phase angles and wavelengths but are incapable of explaining multi–filter phase functions.

TM: Yet, such simple models have been very successful for determining sizes of many targets. But these simple models have clearly many shortcomings when trying to do reliable thermal and physical characterization of small bodies.

2.3 Talk: Kührt

Ekkehard Kührt gave a talk on *Minor bodies at DLR (Berlin)*. The presentation can be found on the Team website.

EK: For Hale–Bopp the CO production rate was proportional to the solar flux.

HR: This does not necessarily exclude crystallization of amorphous ice as the underlying mechanism responsible for CO release, if that process in reality is endothermic instead of exothermic.

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EK: Thermophysical models using spherical craters is very flexible and highly accurate since analytical solutions to the crater–wall temperature distribution can be made.

HR: The spherical crater model still has some limitations regarding the level of roughness one can be created.

We had to break before a thorough discussion on Ekkehards talk since we had a Team dinner reservation at *Restaurant Harmonie*, where we enjoyed a very nice fondue.

3 Day II

We started the day by discussing various aspects of Ekkehard's talk.

TM: Concerning diurnal versus orbital heat waves – what is the lowest temperature we can expect on asteroids? Many models do not include orbital thermal evolution, which should yield nonphysically low temperatures for regions on asteroids experiencing polar nights.

EK: We include it in our models, with timesteps on the order of minutes throughout the entire orbit to capture the temperature evolution on the entire surface. Generally, the orbital heat wave is not so important.

BD: Even if one takes the seasonal heat wave into account, one still has to decide on how to deal with initial conditions and number of orbits calculated before the simulations are compared with observations. How do yo deal with that?

EK: We use arbitrary initial conditions and evolve the target for 2–3 orbits to reach equilibrium (defined as a fixed temperature being achieved at a certain depth).

TM: Lutetia has very low thermal inertia. Night temperatures drops to very low values (20 K), but this ignores heat coming from inside.

BD: What about assumptions regarding internal structure, compaction due to gravity etc – it all affects the modelled heating from the interior?

EK: The quality and abundance of observed data sets the limit on how detailed the model needs to be.

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TM: You mentioned your observing program at Calar Alto?

EK: We have 100 nights per year, Stefano Mottola is the PI, we are e.g. looking for binaries in order to perform mass and density measurements. The telescope is automatized, has a 1.2 meter mirror and the limiting magnitude is about 19.

BD: Joseph Trigo–Rodriguez and his colleagues has a long term monitoring project for Schwassmann–Wachmann 1. Is that something that could be studied also from Calar Alto, e.g. triggered by alerts when there is an outburst?

TM: It would also be valuable to perform observations of the Hayabusa–2 target 162173 (1999 JU_3).

EK: We are happy to receive suggestions for projects, and we will see what can be done.

HR: This is exactly the kind of program we would have liked to have ten years ago when studying the (S–W 1) CO line. We found that CO primarily originated at the subsolar point, in subsurface layers but close enough to surface to be triggered by diurnal heat wave.

EK: There are very different interpretations of the large outburst of comet Holmes, some favoring amorphous ice, others do not.

3.1 Talk: Davidsson

At this point, Björn Davidsson gave a talk on *Thermal inertia and surface roughness of Comet 9P/Tempel 1.*

TM: Disentangling thermal inertia and surface roughness should be very difficult at the short wavelengths (3–5 μm) at which 9P/Tempel 1 was studied. It is more reliable to deduce thermal inertia from integrated photometry, while considering a large phase angle interval.

BD: I agree that the task is very difficult, and it may be impossible to disentangle thermal inertia and surface roughness. A successful analysis depends on your goals – even if we only manage to set e.g. upper limits on thermal inertia, it could still be valuable. We are a bit puzzled by an apparent dependence, for our (family of) solutions, on location on the surface but we are not sure if we see differences between morphological units or just a dependence on incidence angle.

TM: I do not expect thermal inertia to change much with location, but perhaps roughness.

BD: Also thermal inertia could change systematically with incidence angle if the heat conductivity is temperature dependent. We are having temperatures at which radiative transport may become important compared with solid state conduction. The apparent increase in thermal inertia that may be seen as the incidence angle is reduced could perhaps be due to this effect.

HR: Radiative conductivity could be important for asteroid regoliths with large grain sizes, but perhaps not for comets.

This concluded our presentations of current activities of Team members. We now turned to discussing the laboratory work we wish to conduct. BD started by showing a couple of slides (see *Laboratory Work* on the Team website) to provoke reactions and start a discussion. The main message was that current databases seem to 1) Lack data on organic materials and space weathered minerals; 2) Lack data at near–infrared wavelengths (shortwards of $5\,\mu$m) in spite the fact that many spacecraft NIR spectrometers operate at such wavelenghts; 3) Lack of data on how emissivities change with emergence angle.

JH: An additional problem with many databases is lack of information on the properties of the studied samples. At the *BED: Berlin Emissivity Database* we accurately keep track of all sample properties and measurements.

JH: We at PEL would like to share our "beta version" of BED within the ISSI Team for feedback and input before going public.

All: This is highly valuable and much appreciated!

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BD: There is often a sloppy terminology in databases, e.g., it is claimed that "emissivity" has been measured, but it is not clear if they refer to hemispherical emissivity, or directional emissivity (and if so, for which emergence angle?

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BD: What can we do in order to improve the situation concerning organic material, to be used as analog material for e.g. D–type asteroids and comets?

JH: We have several meteorite samples as well as graphite on our list of materials to investigate. For other organics, we need to have ideas on what to use, and how to manufacture it? We have various chemical companies in Berlin area that study organics.

HR: It would be great to have a sample of Tagish lake.

All: It was agreed to do our best to get our hands on a sufficiently large sample of the Tagish Lake meteorite. A thorough study of its bidirectional reflectance at optical wavelenghts, as well as its emissivity from $3\,\mu$m and upwards (to $200\,\mu$m and potentially higher) would be an important contribution from the ISSI Team, and would make a good publication.

JH: We have worked hard to push our equipment to allow emissivity measurements down to $3\,\mu$m and we may even be able to push it further, to $1\,\mu$m.

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EK: It is not only optical properties that are of importance here, but also measurements of heat conductivity in porous dust. I suggest you invite Jürgen Blum, who is very active in this kind of experiments.

All: We all agreed this was an excellent proposal.

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BD: Would it be possible to measure emissivity versus emergence angle?

JH: This has to be investigated. The equipment could potentially be modified rather quickly for this, at least if only considering rotation along a single axis.

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TM: In many investigations, a thermal infrared emissivity of 0.9 is used by default. What is the origin of this canonical value, and how can we motivate its usage?

JH: Many minerals display this behavior, as shown in laboratory experiments.

BD showed Fig. 11 from Davidsson *et al.* (2009), Icarus **201**, 335–357, with calculated emissivities versus wavelength for different grain sizes and material, with a strong preference for emissivity in the 0.8–1.0 range at 10 μm and beyond, for most considered cases.

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BD: What about measurements at sub–mm wavelengths? Can we investigate if there indeed is a significant drop in emissivity at large wavelenghts? Can we verify or disprove Keihms explanation experimentally?

TM: We see emissivity drops at sub–mm wavelengths both for Vesta and for TNOs.

JH: We could definitively do this at PEL.

BD: I saw that you had access to samples from Millbillillie (an eucrite, which most likely originates from Vesta) at PEL. This would be a good starting point to investigate the emissivity behavior at large wavelenghts.

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TM: How large is the contribution of scattered solar radiation at NIR wavelenghts?

BD: In our Tempel 1 work we need to subtract the reflected fraction from the total observed spectrum, to isolate the emitted fraction. We do this by either assuming the same reddening slope as measured at visual wavelengths, or to introduce spectral neutrality beyond a certain wavelength, since D–type asteroids often display such a strong reduction of the spectral slope around 3 μm (assuming that D–type asteroids are reasonable analogs for Tempel 1). Our results depends very little on the different slopes we assume, and the location of the breaking point, indicating that the contribution from scattered radiation is small.

After the general discussion about laboratory work, we made decisions on what laboratory work to perform (see "Action Items" below).

Progress report by BD on the project *Roughness – Level of complexity* (see the Team website for the presentation).

TM: Around $3\,\mu$m, where the spectrum is dominated by the hottest parts of the surface, is it really crucial how a model deals with shadowing and self heating?

BD: This is where we have the largest difference, some 30% in intensity.

EK: It is important also to consider emergence angles other than zero (nadir), and also investigate the dependence on the angle between the incidence and emergence planes.

Progress report by BD on the project *Roughness Type* (see the Team website for the presentation).

EK: I am willing to share my model results on cratered surfaces.

After the lunch break, TM presented a progress report on the project *Roughness versus wavelength and phase angle* (see the Team website for the presentation).

Progress report by BD on the project *Roughness disguised as* $\varepsilon(e, \lambda)$ (see the Team website for the presentation).

Progress reports by BD on other projects, for which little work or no work has been done so far (Database; Nomenclature document; Nightside properties, Blind Test). TM presented the Team website.

During and after these presentations, the following issues were discussed.

Concerning the *Nightside properties* project: TM is interested in studying the effect of nightside emission for various thermal inertia, but recognize that unmodeled seasonal effects may be a problem. BD suggested that one replaces the lower boundary condition from zero gradient, to a fixed and low (but arbitrary) temperature as a first order correction.

Concerning the *Blind test* project: What is really the goal of this project (generating synthetic observational data with one model, analysing it with other models to see if correct parameters are recovered)? One application is to see if and when one can break the degeneracy between roughness and thermal inertia. In particular, it is important to investigate if the real phase angle restrictions applicable to NEAs, MBAs and Trojans are sufficient for such a separation. Another reason is to see what active sublimation (e.g. for TNOs) affects the results.

TM: One of our most important tasks is to demonstrate that roughness actually is needed to explain observations. This is clear e.g. for Phobos and Lutetia. Herschel observations of Lutetia are completely impossible to match to modeled thermal emission from the flyby shape model, if the model facets are considered flat. A thermal inertia below 20 MKS is required.

BD: With all the work that has been done on interpreting asteroid thermal emission, is there really no systematic study showing that roughness actually is needed?

TM: It is not uncommon to see investigations where roughness is neglected (e.g. the first MIRO interpretations of Steins observations), so it is certainly not considered mandatory.

BD: Often there is a learning curve, many people start with the simplest possible models, e.g. assuming flat surfaces below the shape model resolution (including myself), but move on when it is seen that it does not work. The problem is also that some people do not believe in complex models with many free parameters, because they consider it possible to fit anything in that way. They prefer models with few free parameter. Therefore it is probably important to demonstrate that certain objects cannot be understood unless roughness is taken into account.

HR: There is a risk in introducing too complex models – Marsden's non–gravitational $\{A_1, A_2\}$ formalism has been challenged by other models containing up to 17 free parameters.

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BD: When Yarkovsky effects are calculated, do people take roughness into account, or just thermal inertia?

HR: Yarkovsky effects have been measured directly for asteroid Golevka. One could check what happens when roughness is included in the model reproduction of the observed astrometry.

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EK: To illustrate why roughness does not play a role at long wavelenghts, remember that its main effect is to alter the effective temperature. The corresponding Planck curves change strongly near the peak, but very little at the large–wavelength tail. Thus, the effect of roughness is difficult or impossible to measure at such wavelengths.

BD: Is there any study that can be made at long wavelengths that is not possible to do at short ones?

TM: When solving for size and albedo, long wavelength observations are important. Only at long wavelengths is it possible to distinguish a cold or warm terminator.

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EK: An η–model may be OK for isolated wavelengths, but does not work when you have observations at many wavelengths.

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TM: Determining the level of roughness observationally seem to be an recurring theme in our discussions, as well as distinguish it from thermal inertia. This topic should be treated in one of our papers, and we should focus on the data sets we have available, and the wavelength regimes that are actually covered by observatories and spacecraft.

4 Day III

We first discussed the Main Theme of Block II, which according to the proposal is "Intercomparison of model output and synergies from targets where we have in–situ data and remote disk–integrated data". While the first part, intercomparison between model output, is a continuation of the modeling projects outlined above, the second part focused on the LRO Diviner dataset distributed by Joshua Bandfield. The general idea of this *Shared Dataset project* is to apply our various modeling tools to the same set of empirical data, to understand when our results differ, and if so why, but also to compare our results with what is known about the Moon from previous detailed studies, including *in situ* investigations by surface instruments. We identified a number of technical questions about the dataset that will be forwarded to Bandfield before we start working.

1. What is the Bond albedo for the selected region on the Moon? (HR: it is probably more important that all modelers use the *same* albedo and emissivity in their models, than the *correct* one).
2. The filter profiles that are provided – how are we supposed to use them? Are we supposed to convolve our synthetic spectra with these filter profiles, to obtain an integrated flux for a wider wavelength region, that we should compare with the empirical intensities?
3. How was the calibration made? If the SEDs used for calibration are very different from that of the Moon, uncertainties may be large.
4. Do we need to worry about radiation from the Earth, in addition to that from the Sun?
5. What do we know about topography in the selected region?
6. It would be good to have a worked example on how to compare the data to model output (e.g., what has JB done already with this dataset?)
7. What is the status regarding confidentiality – should this dataset be kept within the ISSI team only?

The second topic of discussion concerned the publications. We identified four papers (with very preliminary titles and content).

• *Handling roughness in thermophysical modeling. I. Dependence of spectral energy distribution properties on topography types.* This paper should focus on the projects “Roughness: Level of Complexity” and “Roughness Types”.

• *Handling roughness in thermophysical modeling. II. Disentangling roughness and thermal inertia in disk–integrated data.* This paper should focus on Thomas’ work on recommending methods for determining thermal inertia and surface roughness when using disk–integrated data.

• There will be one or several papers summarizing the laboratory work. The area of activity falls into three topics; 1) Bidirectional reflectance and emissivity spectrum of D–type asteroid and comet analog materials (primarily *Tagish Lake*; 2) The long–wavelength emissivity of Vesta analog materials (primarily eucrite *Millbillillie*); 3) The directional emissivity, particularly in the 3–5 μm region for silicates and the meteorites mentioned above. We need to discuss whether we can cover these topics in a single publication, or if we should split it into two or more.

• The project “Roughness disguised as $\varepsilon(\lambda, e)$” may be part of a paper by Davidsson & Rickman focusing on a description of their thermophysical model.

In addition, there may be other publications, e.g. focusing on the retrieval of parameters from the LRO Diviner data. Alternatively, a “final” paper were we try to address the key issue, as stated in the name of the proposal – how to derive physical parameters from the thermal emission. What have we learned from our various investigations?

We agreed that it is important that our theoretical projects are coupled to “real” problems. For example, the project “Roughness disguised as $\varepsilon(\lambda, e)$” was inspired by the TES and THEMIS observations of Mars, presented by Bandfield (2009), *Icarus* **2009**, 414–428, showing that emissivity spectral behavior changed systematically with emergence angle for specific terrains under constant incidence angle. It may be more challenging to find justification for e.g. the “Roughness Type” project, but it is worth looking at the Earth Observation literature to see if there are examples of systematic difference in thermal emission behavior between completely random terrain (e.g. mountain areas) versus terrain that have systematic geometric properties (e.g., long but narrow Seif dunes).

Other things that were discussed:

• HR: according to ISSI we should have funding for two short meetings, alternatively a single long one.

• All: The next meeting should take place in late September or in October, but we should check when the DPS and EPSC meetings are held and plan accordingly.

• All: It would be good to have a telecon in between meetings, to get going. For example, a telecon during the first half of June, with the goal of discussing the publications, deciding who will contribute with what etc.

• All: We may consider placing some of our results on a website available to the public (general scientific community), even when the results are not "publishable" for various reasons.

• HR: Should we keep Phobos in the database in spite of the Fobos–Grunt failure? (It was agreed we should keep it).

• TM: Björn should ask for contributions to the Nomenclature document.

• TM: It would be good to collect a reference list to key papers on the website.

• TM: It is important to find out whether it is possible to determine that a body is a rubble pile from thermal observations.

5 Action Items

A number of *new* Action items were defined. This does not mean that we should forget about the *old* ones in the last Minutes!

1. Action item BD: Contact Joseph Trigo–Rodriguez to inform him of Ekkehard's Calar Alto program.
2. Action item JH, HR, BD: Acquire a sufficiently large sample of the *Tagish Lake* meteorite for measurements at PEL.
3. Action item BD: Check with Harold Linnartz in Leiden to see if they have "yellow stuff" residuals from their ice irradiation experiments what we could study as organic material analogs.
4. Action item JH: Make a beta–version of the PEL archive available to the ISSI team within a two month timeframe.
5. Action item JH: Investigate if and how the current equipment can be modified to measure emissivity versus emergence angle, within a one month time frame.
6. Action item JH: Initiate sub–millimeter wavelength emissivity measurements on meteorite Millbillillie, within a two months timeframe.
7. Action item BD: Write minutes, and announce telecon when distributing minutes.