MINUTES
THERMAL EMISSION MEETING #4
Third Meeting at ISSI, Bern, March 12-15, 2013

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April 3, 2013

Contents

1 Participants and Background

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

1. MTC: Maria Teresa Capria (IAPS/IASF, Rome, Italy)
2. BD: Björn Davidsson (Uppsala University, Sweden)
3. JE: Joshua Emery (University of Tennessee, Knoxville, USA)
4. OG: Olivier Groussin (Laboratoire d'Astrophysique de Marseille, France)
5. PG: Pedro Gutiérrez (Instituto de Astrofísica de Andalucía, Granada, Spain)
6. AM: Alessandro Maturilli (DLR Berlin, Germany)
7. TM: Thomas Mueller (Max–Planck–Institut für extraterrestrische Physik, Garching, Germany)
8. HR: Hans Rickman (Uppsala University, Sweden / PAN Space Research Center, Warsaw, Poland)
9. MW: Magdalena Wilska (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 2011. 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.

• May 2–4, 2012 at ISSI in Bern, Switzerland: Follow–up on modeling projects, definition of laboratory projects, first discussions on publications.

The current meeting was held at ISSI in Bern, Switzerland on March 12–15, 2013, organized and chaired by Björn Davidsson and Hans Rickman. The purpose of the meeting was to summarize current activities of the participants (Day I); discuss in detail the content and structure of Papers I and II, including new action items (Day II); discuss the status of additional projects and potential additional publications (Day III).

2 Day I

HR, BD: Welcome words, summary of Agenda. The focus of the current meeting is to define the contents of the two papers that summarize the bulk of work made by the ISSI Thermal Emission Team.

2.1 Talk: Capria

Maria Teresa Capria gave two talks; *Dawn at Vesta: VIR data* and *Dawn at Vesta: Derivation of thermophysical properties from temperature data.* Since most 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 comments were made during the talk.

OG: It is very surprising that IAU can block the posting of data on the PDS just because of disagreements over the applied coordinate system.

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MTC: Chris Russell likes what is being done at ISSI, which means increased freedom for me to initiate collaboration within the ISSI context.

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TM: The global thermal inertia average of 30 ± 5 MKS agrees very well with what I and Johan Lagerros obtained for Vesta (Mueller & Lagerros 1998, A&A 338, 340, table 4).

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MTC: We see emission from areas that formally (i.e., according to the shape model and the spice kernel) are located on the nightside. It corresponds to a brightness temperature of 180–220 K.

OG: Did you check the visual image to confirm the radiation is really originating from the night side?

BD: The lunar terminator has illuminated mountain peaks on the night side. Also, what if some solid rocks on the surface with high thermal inertia still are warm on the nightside, providing some signal?

JE: There should be nightside data for the Moon (LRO Diviner) to compare with.

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MTC: There is a tendency that the derived thermal inertia is lower on the northern hemisphere which is colder, compared to the southern hemisphere which is hotter.

OG: It is not very convincing that thermal inertia correlates with latitude.

MTC: We also see a tendency for thermal inertia to be reduced near shadows, where the surface is cooler.

BD: We think we see an increase in thermal inertia with decreasing incidence angle (i.e., raising average temperature) on Tempel 1, perhaps due to an increased contribution of radiative transfer to solid state heat conduction.

MTC: We account for such a temperature–dependence already.

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OG: The Wien regime, at the short–wavelength wing of the Planck curve, is very sensitive to the presence of hot spots. Therefore, the sub–pixel resolution temperature distribution is the *key* in order to understand the thermal emission. The good thing about Vesta (not available for Tempel 1) is that we have very high resolution images that could be used for calculating the temperature–distribution on small scales. It is important to explore if that can explain the thermal emission seen through pixels at lower resolution.

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MTC: A benefit with Rosetta compared to Dawn is that MIRO can help us characterizing the near–surface interior. In combination with VIRTIS measurements of emission from the surface itself, we stand a better chance of measuring the thermal inertia.

BD: Another benefit is that Philae can provide ground truth. A crucial test of the suitability of thermophysical models is that they manage to reproduce the remote sensing data for the correct physical parameters.

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TM: A classification of parameters is needed. Some are physical properties of the target, others are things we measure (e.g. size versus flux). Some physical properties do not change (e.g. topography and roughness), while others change constantly (temperature, as well as temperature–dependent quantities such as specific heat capacity or solid state conductivity).

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TM: Two comments: The Vesta shape models from DAWN are still not released; The thermal NIR spectra from DAWN end at 5 micron where roughness, emissivity, TI, etc have large impacts.

2.2 Talk: Maturilli

Alessandro Maturilli gave two presentations; *Planetary Emission Laboratory Database*, as well as, *Emissivity versus emergence angle at PEL. Millbillillie emissivity.* Since most 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 comments were made during the talk.

AM: The directional emissivity for Millbillillie (nadir viewing) fluctuates around $\varepsilon = 0.6$ with 0.05 amplitude, then raises gradually to $\varepsilon = 0.95$ around $\lambda = 13\,\mu$m where it remains for the entire $13 \leq \lambda \leq 100\,\mu$m interval.

All: These measurements are extremely valuable, as it lends support to the proposal that strong emissivity drops at large wavelengths seen in some modeling, is an artifact due to increased (un–modeled) visibility to the near–surface interior.

AM: There is a difference between the measured emissivity ε and the quantity $1-r$ obtained from measurements of the reflectance r, i.e., the Kirchhoff law $\varepsilon = 1 - r$ is not fulfilled.

BD: What about random and systematic errors in the measurements? Are you sure the $\varepsilon \neq 1 - r$ result is not due to measurement uncertainties?

AM: The measurements have a high degree of repetitivity, i.e., errors are small. Perhaps anisothermal conditions are responsible, in spite of our efforts to consider isothermal samples.

BD: Since we do not measure emissivities and reflectances integrated over the upper hemisphere, but only directional quantities valid for a single solid angle, we cannot expect to obtain $\varepsilon = 1-r$ even for isothermal media. For example, if one of the quantities is isotropic while the other is not, this will directly break Kirchhoff's law.

OG: Kirchoff's law may not be perfectly upheld, but the results are so similar that it should have little practical importance.

JE: For mineralogical interpretation, this is concerning.

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TM: Are the 100 μm measurements independent of grain size? Very low emissivity values are found in submm/mm observations, perhaps due to grains being of similar size?

BD: Millbillillie is a eucrite, a material primarily found near Vesta's equator. What about the howardite (and for Rheasilvia, diogenite) that dominates the rest of the surface – perhaps they have a different sub–millimeter behavior?

JE: We do not see a change in emissivity when the wavelength cross the grain size.

TM (note added after first Minutes draft): *I think the previous statement by JE is very important and should be highlighted!* Was that statement made by Josh or by Alessandro? If this statement is really true then the interpretation of apparently lower observed emissivity for asteroids is related to different thermal properties of the sub–surface layers (like a higher effective thermal inertia related to a more compact/higher density layer and/or higher thermal conductivity). Maybe it would be worth to follow up on this statement with Joern?

2.3 Talk: Davidsson

After lunch, Björn Davidsson gave the presentation *Surface roughness on size scales smaller than the thermal skin depth – Effects of 3D heat conduction on thermal emission.* Since most 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. Since the speaker is unable to talk, write and think simultaneously, there is no record of issues raised during the presentation.

2.4 Talk: Emery

Joshua Emery gave a talk on *OSIRIS–Rex and 1999* RQ_{36}. Since certain content is not for public eyes, this presentation is *not* available on the website. The following discussion took place during and after the presentation.

BD: The surface is mapped seven times per day, so that the same terrain is measured at different local times. Will the viewing geometry be nadir or a mixture of emergence and azimuth angles?

JE: We will try to do nadir.

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BD: What nominal thermal model will be used?

JE: This is still being decided.

BD: The crater model is standard in disk–integrated observations, but has never been used for analysing disk–resolved data as far as I know. This is both surprising and concerning.

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Background: 1999 RQ_{36} has a 1/2500 chance of hitting Earth in the late 2100's (one of the highest probabilities of any PHA). It is 525 m in diameter, has a 4.29746 hour rotation period, a retrograde spin with known pole, and is most likely carbonaceous (B–type). Three radar passes resulted in a shape model (including a rather pronounced equatorial bulge). Thomas used Spitzer, Herschel, and VLT data to derive a thermal inertia of 350–950 MKS with the correct spin pole. Others obtained 600±50 MKS which led to a density estimate of $1\,\mathrm{g\,cm^{-3}}$ in order to explain the observed Yarkovsky effect.

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TM: In reflected light you see the entire cross section, which makes it suitable for shape reconstruction via light curve inversion. In the thermal infrared, you only see a subset of the body that is hot. For this reason, the thermal lightcurve can differ substantially from the visual one, and both provide important constraints on the properties of the body.

OG: Equatorial bulges are often interpreted as land slides from the polar regions towards the equator caused by spin–up, but this shape shows up more frequently in radar echo reconstruction, than in visual lightcurve reconstruction. In some cases it may be an artifact.

BD: Would it not be possible to generate synthetic bodies with or without equatorial bulges, calculate the corresponding radar echo with noise added to it, and see if standard reconstruction techniques manage to retrieve the true shape.

OG: It is always difficult to get the feeling for the uncertainties in a shape model by visual inspection.

HR: If the suggested connection with this asteroid to the Polana family keep in mind that the members in the Nysa–Polana group displays a large albedo variation. The Almahatta–Sitta meteorite, possibly linked to the Nysa–Polana is a big mixture of material, perhaps sampling both objects.

2.5 Talk: Groussin

Olivier Groussin gave a presentation on the *Effects of Roughness; Effects of the position of the observer; The temperature, thermal inertia, roughness and color of the nuclei of comets 103P/Hartley 2 and 9P/Tempel 1*, Since most 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 comments were made during the talk:

JE: Why was only two out of three water bands seen in Tempel 1?

OG: This is a particle size effect, showing that the icy grain cannot be smaller than 20 μm.

3 Day II

3.1 Paper I

The forenoon activities focused on the content and outline of Paper I. OG collected the result of discussions into a separate file (ISSI_PaperI_outline.pdf), distributed together with this Minutes and available on the website. The outline also contains lists of responsible persons for each section and subsection of the paper, as well as deadlines (the most important ones being completion of simulations by end of June 2013, and completion of a first draft by end of September 2013, well in advance of the next Team meeting to be held in November 2013). All team members should be offered to be on the authors list, with a minimum requirement to read and comment on the draft. The order should be Rickman plus all others in alphabetic order, or alternatively; Rickman, Davidsson, plus all others in alphabetic order. The paper should be submitted either to *Icarus* or to *MNRAS*. The following issues came up during discussions.

TM: We need to define the size scale of roughness.

OG, BD: For resolved bodies the upper limit is just under the pixel resolution, which could be tens of meters, even a few hundred meters. The smallest scale is where we still see temperature dispersion due to shadows, not leveled out by lateral heat transfer. That scale depends on the heat conductivity, and can be measured in centimeters to decimeters for solid rock, but in millimeters for regolith. For all practical purposes, it is the roughness on 1–100 meter size scales that are of real importance for thermal emission.

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OG: When the temperature distribution on a rough surface changes, is it necessary to calculate self heating iteratively?

PG: In my code, the temperature distribution of the previous time step is used to calculate the self heating flux contribution at the current time step. This procedure is accurate as long as the time steps are small enough.

BD: In our code, we have the option of iteratively updating the self heating fluxes a number of times between actual time steps. However, tests show that there is no practical difference between doing one or several iterations.

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OG: Although different codes are contributing to Paper I, we should stress that the comparison is made between different types of surfaces, *not* between the codes themselves. All codes basically solve the same physical problem, and there are no reasons to doubt this is made properly. Only minor differences regarding implementation exist (except regarding lack of self heating in the fractal model, but this may be possible to implement in time for the paper).

MTC: The introduction of the paper is particularly important. We need to explain carefully why we make this study and why we think it is important.

PG: It is important that all the terminology we use is well defined and well described. We should have an appendix with definitions and descriptions, perhaps even a self–standing paper on this, for future reference.

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As an illustration to the last point, it turned out that OG and PG had used different definitions of the azimuth angle in their simulations, so we need to agree on one system, common for everybody.

After lunch, we switched the discussion to Paper II. Since this paper focus on disk–integrated observations (and modeling thereof), we had postponed Thomas Muellers science presentation to this point. Thomas first presented his talk, then his ideas on Paper II.

3.2 Talk: Mueller

Thomas Mueller gave a presentation on the *Thermophysical modeling of small bodies on basis of disk–integrated thermal measurements*. Since most 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 comments were made during the talk:

TM: The Itokawa shape model is available in four different resolutions from the PDS: http://sbn.psi.edu/pds/resource/itokawashape.html The 4 resolutions correspond to $(Q+1)^2$ vertices and Q^2 facets, with $Q = 64$, 128, 256, 512. At least the lower resolution models require still the addition of model roughness to explain the observed fluxes. So far, I was not able to use the highest resolution model.

OG: Topography and albedo are difficult to disentangle with the method Gaskel is using (shape obtained from shading), i.e., it is not pure stereo like the method used at DLR. A non–uniform albedo may be misinterpreted as slope.

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TM: Pluto has dark spots in the visible that are bright in the infrared, i.e., hot.

OG: For Tempel 1 and Harley 2 the dark spots are actually cooler than the rest of the surface, since they are smoother.

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PG (commenting on the O'Rourke *et al.* map of Lutetia with a single temperature assigned to each facet of the macroscopic shape model): For a rough terrain there will be a distribution of temperatures that cannot be represented by a single (physical) temperature.

TM, BD: The model of Johan Lagerros should contain a full account of roughness per facet of a macroscopic body (either from a crater model or a random Gaussian model). However, none of us are sure on the spot how it is implemented, or what the temperature map means (brightness temperature?).

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MTC: is a thermal inertia close to 1000 realistic for any body in the Solar System?

TM: yes, some small NEAs seem to require such a high thermal inertia to explain the before/after opposition asymmentries.

3.3 Paper II

Hand Rickman reported on a talk with Dr. Falanga. He said the final report is supposed to be 1–2 pages about how we think things went during the project, with references to submitted papers etc. In principle it is possible to prolong the grant, if we find strong reasons to continue. ISSI do not have demands regarding journal of submission, but they do not have money to support color figures.

At this point, our attention turned to Paper II. Some points raised before heading to the team dinner at Harmonie (discussion continued on Day III).

JE: It is difficult to get observing time on big telescopes in order to measure thermal lightcurves. If we can write a paper that demonstrates what we could achieve by having a thermal lightcurve, it could be used as "ammunition" in proposals. This could perhaps be done for Lutetia or Eros.

TM: There are some critical questions that should be addressed in the paper, one way or the other. What data are strongly affected by various parameters (e.g., when and how can we expect the measured flux to be strongly dependent on specific properties of the body, e.g. roughness). What are the critical measurements and what do they tell us about the object itself? The paper provide recommendations on what is the best way to observe, provide warnings about traps to fall in, and discuss limitations on the accuracy of derived thermophysical parameters.

4 Day III

We started the day by continuing discussing Paper II. Note that additional comments and discussions concerning Paper II are available at
http://www.mpe.mpg.de/∼tmueller/issi/paperII_v1.pdf

TM: We should study a few concrete examples, for which we have plenty of groundbased and spacecraft observations, e.g. Itokawa. In addition to a good shape model from Hayabusa, we have thermal lightcurves from ground, as well as disk–resolved observations from Akari and Spitzer (the latter has data for 8 rotational phases).

BD: What approach should we use? One alternative is to use the known shape model and spin axis and predict flux as function of wavelength and phase angle, for various assumptions on thermal inertia and roughness. Comparing with observations we could e.g. demonstrate insufficiency of the zero roughness assumption, but also show how small the error bars in observations need to be to e.g. disentangle thermal inertia and roughness.

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BD: What does it mean that a model "works"? For Tempel 1 we could fit all the available data with a very simple model (each facet on the globally irregular shape model treated as a flat surface with a temperature obtained from a 1D model balancing insolation, thermal emission and heat conduction). However, the parameters we needed to use to obtain the fit were untypical (very low thermal infrared emissivity, very high thermal inertia). In a sense, the model worked because data was reproduced. In another sense, the model did not work because one could doubt that the parameter values were realistic. How do we decide when derived physical parameters are acceptable or not?

TM: Problems may arise when there is not enough empirical data to truly demonstrate that a particular model is unfit for the job. However, when there is a wealth of data, and the model manages to reproduce all of it, we may have confidence in a model and the derived parameters and say that it "works".

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HR: What is the first step towards a paper? To carry out the simulations and data analysis?

TM: The first step is to assemble all known data.

PG: As part of the database project, I assembled a lot of data for Lutetia that could be considered for the analysis.

MTC: VIRTIS data could be added as well.

PG: Is there unresolved VIRTIS data?

MTC: Perhaps not, we were mostly interested in resolved observations

TM: The best shape models and spin solutions we have are for Itokawa, Lutetia, and Eros. The major part of the work is to get all data into a shape suitable to do the study.

Additional issues that were discussed:

Next meeting

HR, BD: We need to decide dates for the next meeting and make a booking very soon.

All: We agreed to make preliminary reservations for Nov 4–7 or Nov 18–21, 2013, in both cases starting either on Monday (which would mean traveling on all Sunday for some) or Tuesday. BD will set up a doodle poll for the final decision.

Asteroids IV

MTC: I think we should make a contribution to the *Asteroids IV* book. Deadline for announcing interest and a brief abstract is end of March. We have the competence and experience to write such a chapter.

TM: We need to define what is new since Asteroids III. One development is the usage of visual and thermal lightcurves to reconstruct shape and spin.

OG: In addition, we have for the first time spatially resolved NIR data for several bodies (Steins, Lutetia, Vesta). This must be part of such a chapter.

TM: There are also new missions, hence new data sets, since Asteroids III. For instance, Herschel, Spitzer, Akari, WISE (but many of these may get their own papers).

JE: The Harris & Lagerros paper in Asteroids III focused on deriving size and albedo. We should focus on the work made to go beyond that, e.g. measure thermal inertia and roughness.

BD: We need a lead author that take charge and make sure that things are getting done. I think Thomas Mueller or Josh Emery are the most experienced and suitable candidates.

All: It was decided to make an attempt, and let TM and JE come up with possible formulations for a chapter proposal for Asteroids IV.

Nightside emission

PG: A $\rho = 20°$ surface has been studied, with thermal inertia in the 25–100 MKS range, viewed from nadir. It turns out that it differs very little from a flat surface (5% in terms of flux).

BD (to TM): Did you ask Johan Lagerros if it would be possible to replace the zero gradient assumption in his code, in order to study the seasonal effects?

TM: here is Johan's reply from 10/Feb/2013: "My code does not support alternative boundary conditions for the interior. I had plans for it long ago, and I think I made some experiments. The tricky part is to make a physically justifiable choice for that boundary condition. From what I remember when doing the calculations, the results were highly sensitive to whatever guess you made for the internal temperature, and at what depth you fixate it, which was not very satisfying (since you then add something arbitrary without any obvious physical meaning). The plan I think I made for this unfinished task was to:

1. Consider dT/dz = non–zero constant at some depth. Somehow I convinced my self that this made more sense from different points of view. At least I think the results should be less sensitive to the depth chosen for lower boundary condition.
2. Make models with seasonal effects, in order to estimate the value of dT/dz at larger depths, as a function of the latitude and the position of the asteroid in its orbit. In the first step one would consider only the average diurnal insolation for any given position in the orbit, and then make a long term model, in order to find the thermal balance spanning over several orbits. Based on that one should be able to tabulate dT/dz boundary conditions.

I could be 100% wrong about all this. After all it is long ago since I made these plans. The seasonal effects could be done using my code base, but not out of the box. A lot of coding and experimenting is needed in order to understand the best way to do this."

MTC: When the thermophysical equations are solved globally, the conditions at large depths are indeed very sensitive to various assumptions regarding the previous thermal history of the object.

BD: Still, MIRO will be able to measure sub–mm emission from parts of the 67P surface that have been in complete darkness for months or years, and it would be interesting to see what that tells us about the deep interior, provided appropriate models are available. The code of Eric Rosenberg and Paul Weissman is very interesting since it do global full 3D heat conduction.

PEL contribution to the ISSI Team

BD: The Millbillillie measurements presented by AM are very interesting, and it would be good if they could be incorporated into our currently planned papers.

OG: They would fit in Paper I, as a motivation for us to assume a quasi–constant emissivity near unity in the thermal infrared and beyond.

TM: Unusually low emissivities have been obtained at long wavelengths when matching models to disk–integrated observations, also for Vesta. The lack of such a drop in emissivity in measurements of Vesta material is an important step forward. Paper II could contain a brief discussion of this problem.

HR: These are good suggestions, but Helbert *et al.* may want to extend their investigation and publish a separate paper, either within or outside the ISSI framework. We should ask them what they have in mind.

Databases

BD: The database with resolved objects that have been observed in the infrared is still half finished. When we finish it, should we keep it for internal use only, or make it publicly available in some form?

TM: It would also be good to have a searchable database for disk–integrated targets, although that would require a skilled programmer.

MTC: The European Virtual Planetary Observatory could be a good place to store the database and guarantee longterm public availability.

Nomenclature document

TM: I also have another wish for the definition/nomenclature document, section 1.4: It would be nice to include also Johan's translation between S into a rms–value. I have included a short table in the updated version of my talk with S/rms values coming out of Johan's code, but I still would like to find out how it is done, what it means and how realistic this is.

5 Response to previous Action Items

1. *Action item BD: Contact Joseph Trigo–Rodriguez to inform him of Ekkehard's Calar Alto program.* Done.

2. *Action item JH, HR, BD: Acquire a sufficiently large sample of the Tagish Lake meteorite for measurements at PEL.* No sample available yet – in addition, the student responsible for this project has been unavailable for months.

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.* Request sent, but no reply.

4. *Action item JH: Make a beta–version of the PEL archive available to the ISSI team within a two month timeframe.* There is a problem with DLR, as they are reluctant to provide public databases for safety reasons. (Comment by BD: Jörn Helbert mentioned that a beta–version to be made accessible only to the ISSI team, i.e., no general access. Comment by JE: if the data is uploaded to PDS, this would solve the security issues of DLR).

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.* The detector cannot be moved. Only the sample can be slightly inclined and measurements for 2.3° inclination were performed and presented.

6. *Action item JH: Initiate sub–millimeter wavelength emissivity measurements on meteorite Millbillillie, within a two months timeframe.* Emissivity measurements at $1 \leq \lambda 100\,\mu$m were performed and presented (see Sec. 2.2).

7. *Action item BD: Write minutes, and announce telecon when distributing minutes.* Minutes written and distributed, but there were no telecon.

6 New Action Items

The following action items were identified in addition to those specified for Paper I.

TM, JE: Formulate a statement of interest for contributing to *Asteroids IV*.

BD: Set up doodle poll for time of next meeting.

BD: Write Minutes and distribute nomenclature document, as well as Oliviers outline of Paper I.

BD: Arrange for telecons regarding Paper I and the nomenclature document.

MTC: For small incidence angle intervals, and if possible, spatially small regions on Vesta, study intensity versus emergence angle to see to what extent the emission is Lambertian.