Herschel Calibration Overview

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Outline

- In the beginning....
  - Instrument requirements/expectations.
- Key areas of flux calibration
  - Planets – "standard" calibration versus Mars?
    - Main calibrators Neptune (e.g. SPIRE-P, HIFI) and Uranus (e.g. SPIRE-S)
  - Stellar calibrators: K and M stars
  - Asteroids: also prime calibrators, legacy? Useful non-linearity calibrators
- Scan maps and mappers
- Cross-calibration between Herschel instruments
- Some external comparisons
  - SPIRE comparisons to Planck data
  - PACS and MIPS extended emission
- Pointing
- Conclusions

In the beginning....

- Requirements and goals for flux calibration

  - HIFI:
    - Absolute flux calibration: 10% requirement; 3% goal

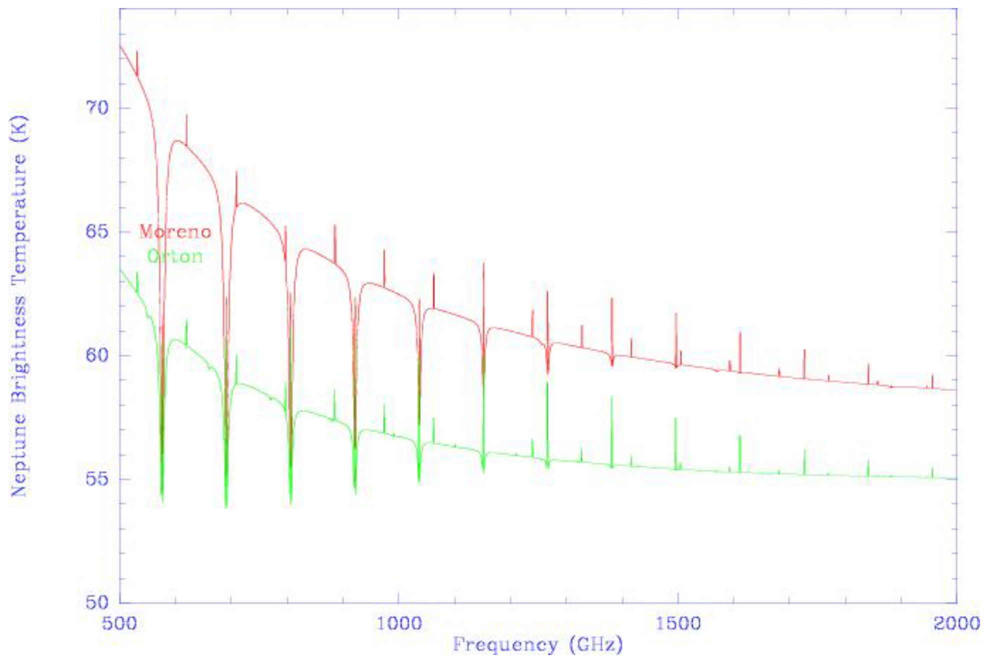
  - PACS:
    - Absolute flux calibration, Photometer: --% requirement; 5% goal
    - Absolute flux calibration, Spectrometer: 20% requirement; 10% goal

  - SPIRE:
    - Absolute flux calibration, Photometer: 10% goal
    - Absolute flux calibration, Spectrometer: 15% goal

Flux calibration: Planets

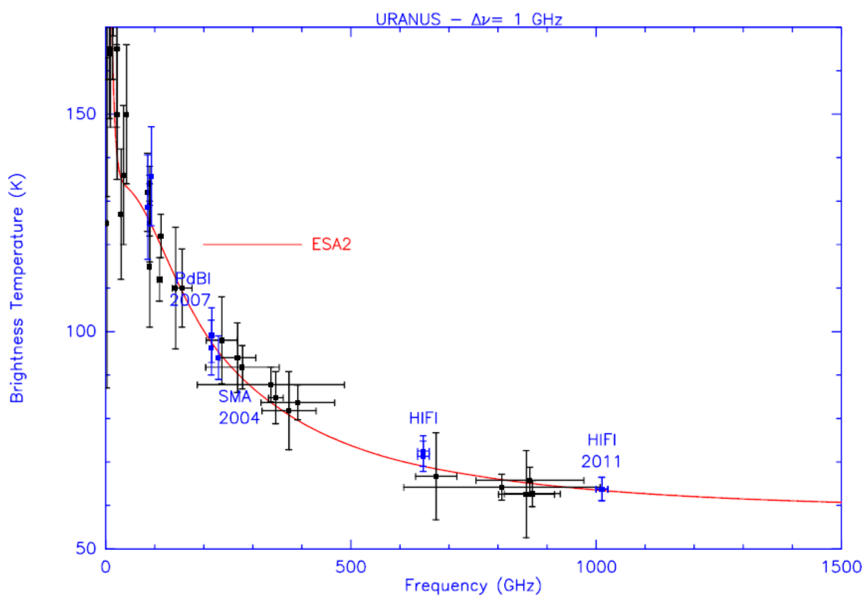
- Used by SPIRE and HIFI.
- Based on physical atmospheric models of the outer planets (particularly Neptune and Uranus for SPIRE calibration).
- Data used for initial models based on physical flyby information, ground based radio to optical measurements, recently Spitzer (IRS) spectral data [Orton] – calibrated against standard stars.
- Work started well before launch.

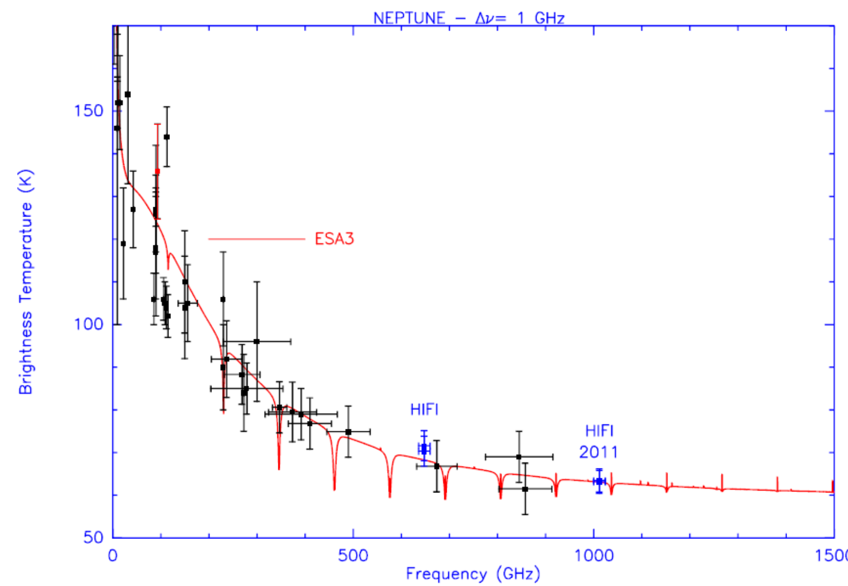
- Uranus reasonable agreements between models – not so for Neptune….
- Major issue constraining P(T) for Neptune.
- Also recognised that feedback from Herschel data would allow iteration on the models.



Uranus and Neptune models

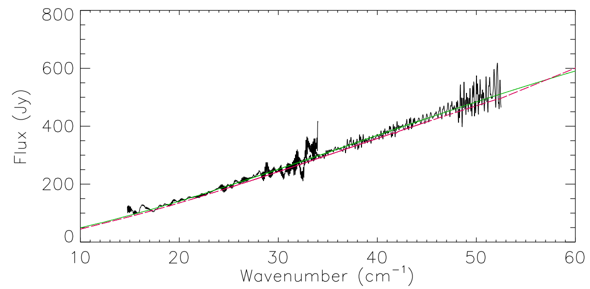
- Models at launch.

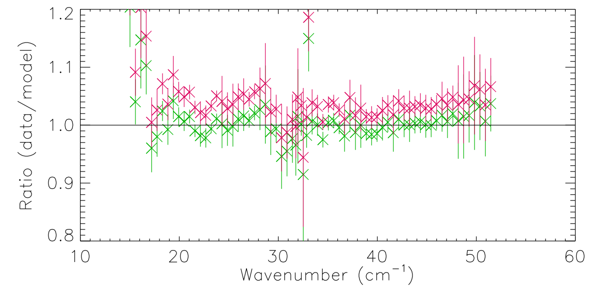


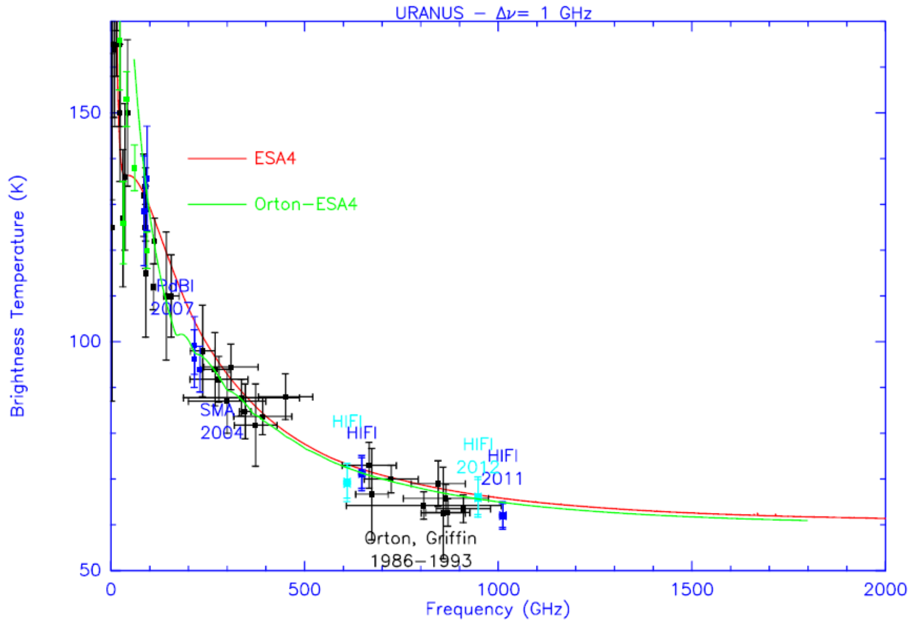


Updates to take into account Herschel data

- Spectroscopy with SPIRE FTS across the whole band provides.
  - Comparison to "calibration" using telescope emissivity + temperature of the mirror versus Uranus models. Orton (ESA4) model in green and Moreno (ESA3) model in red.



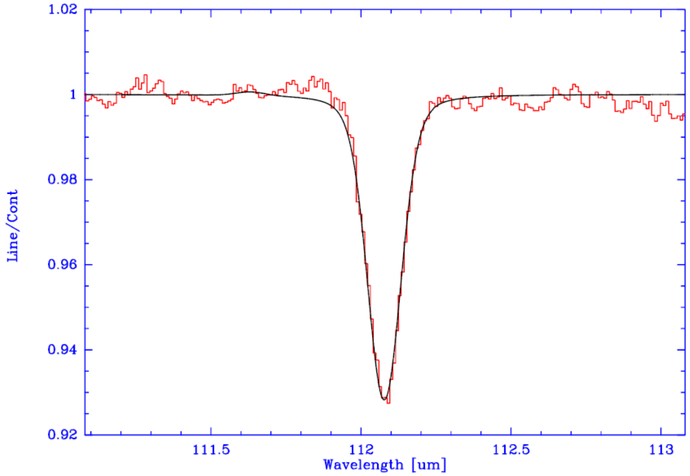


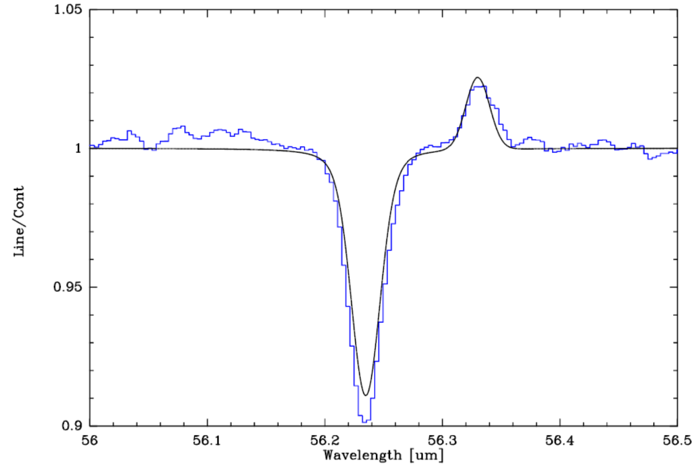


Small differences (~1%) in Uranus models, depends on H_2S content of atmosphere. 3-4% increase in planet model flux since beginning of launch.

Uranus constraints/checks with PACS HD line measurements

- PACS HD lines provide constraints to model. Reasonable fit at 56 μm, not quite so good as at 112 μm. Maybe slightly higher stratospheric temperature indicated as compared to used in ESA4 model (Feuchtgruber et al 2013, A&A, 551, 126).

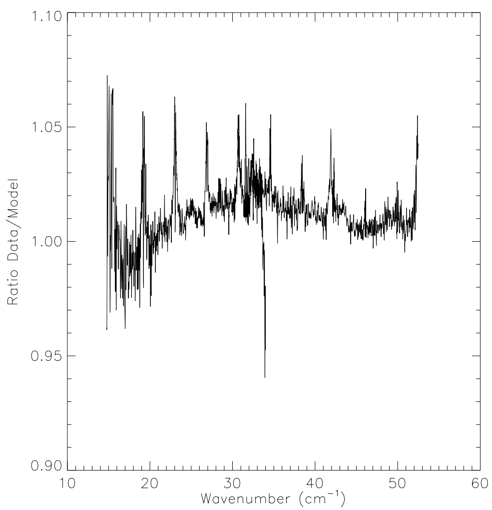




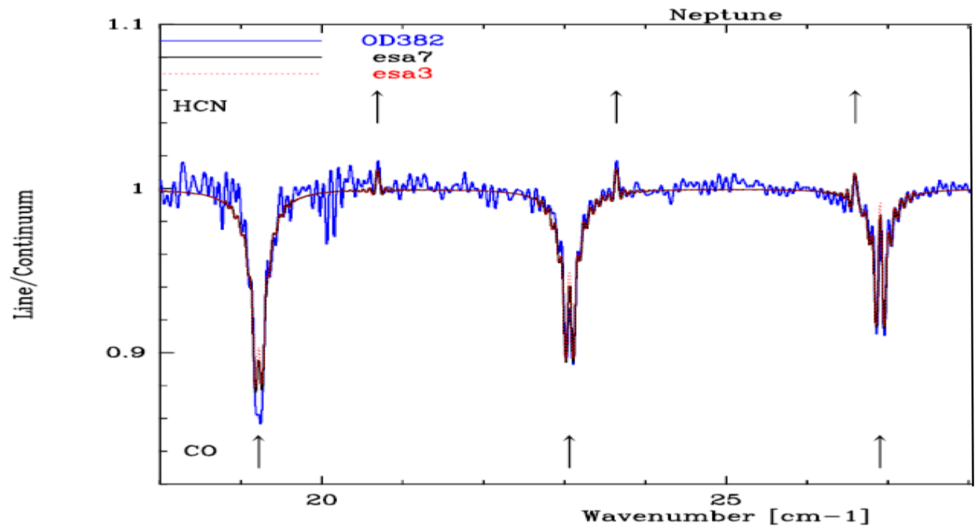
- **See presentation by Glenn Orton**

Neptune models

- Similar comparisons to telescope mirror spectra show excellent agreement between model and mirror flux, but CO lines could be better modeled.



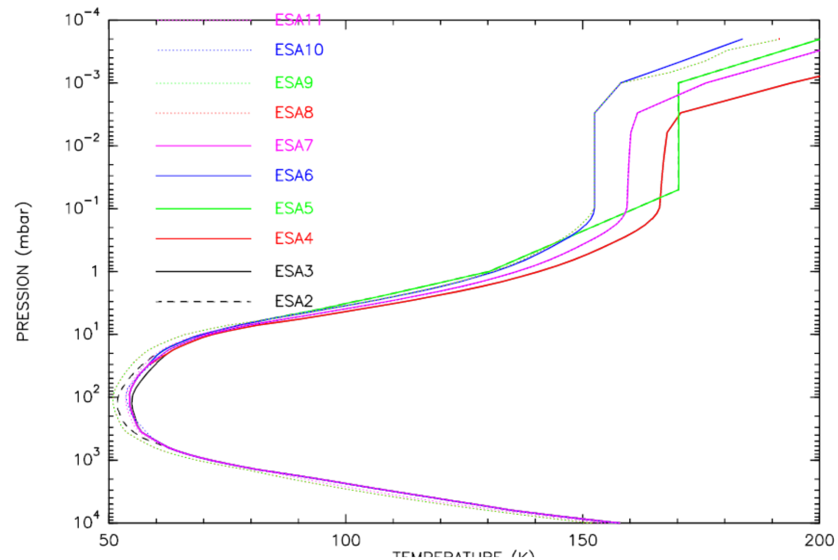
Neptune/CO - SPIRE



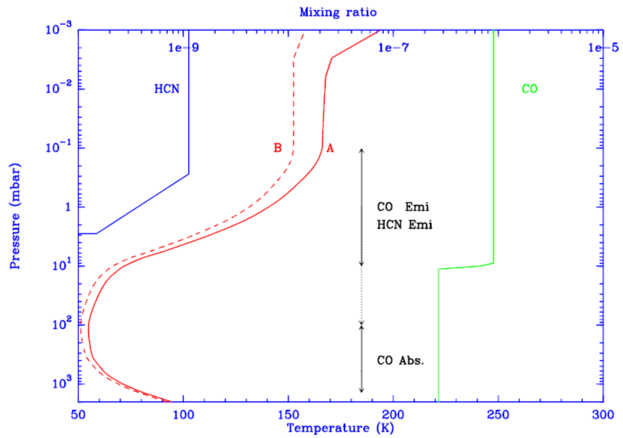
Need to modify the deeper tropospheric temperature to better fit the CO lines (on going work) – SPIRE probe deeper than PACS 13

Series of New Models

Series of new Neptune atmospheric models being tried with slightly different Pressure/ Temperature profiles.



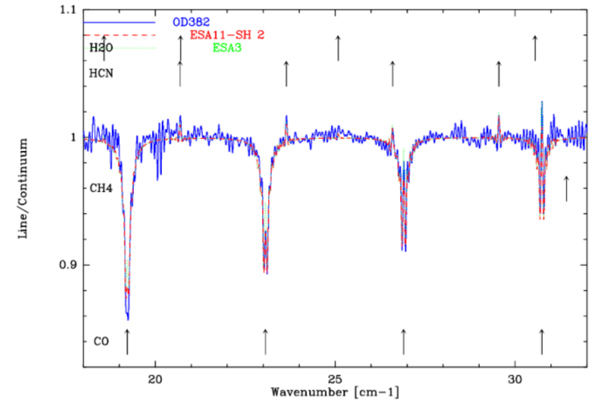
Also a variable for pressure at which CO mixing changes (evidence of ancient comet collision?)

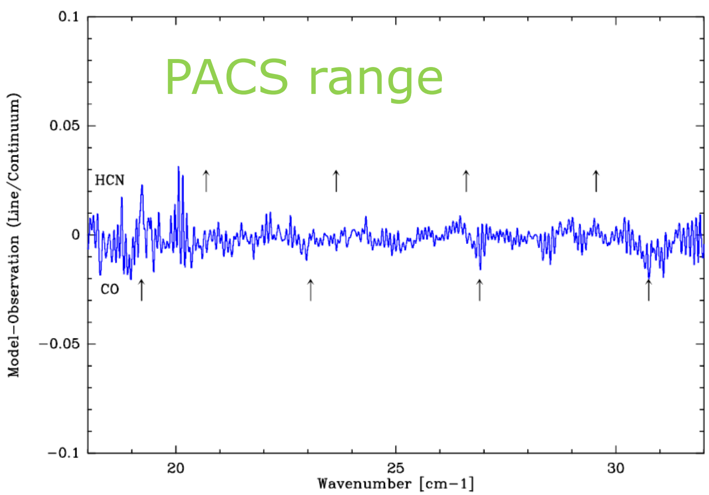


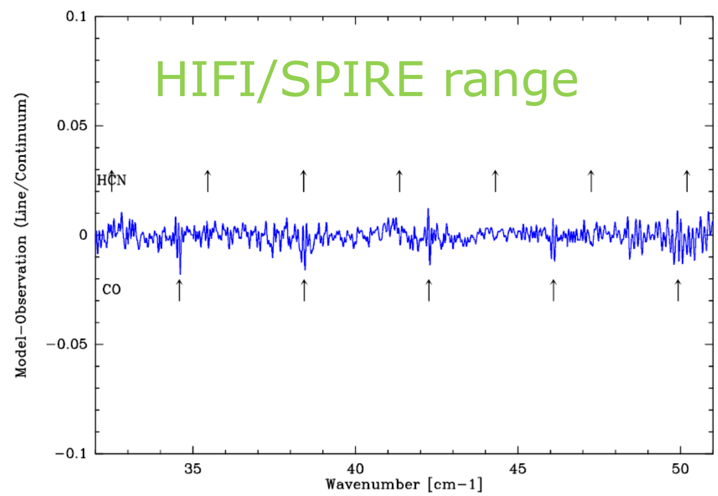
Fitting of CO lines with new models

ESA11 model comparison to absorption line spectrum seen by Herschel.

Residuals for PACS and SPIRE ranges look good.







Towards the next Neptune model (ESA4)

Best model reported to date by Raphael is “ESA 11”. Difference between this and current model in the system (ESA3) is minimal in terms of flux across the whole PACS/SPIRE range

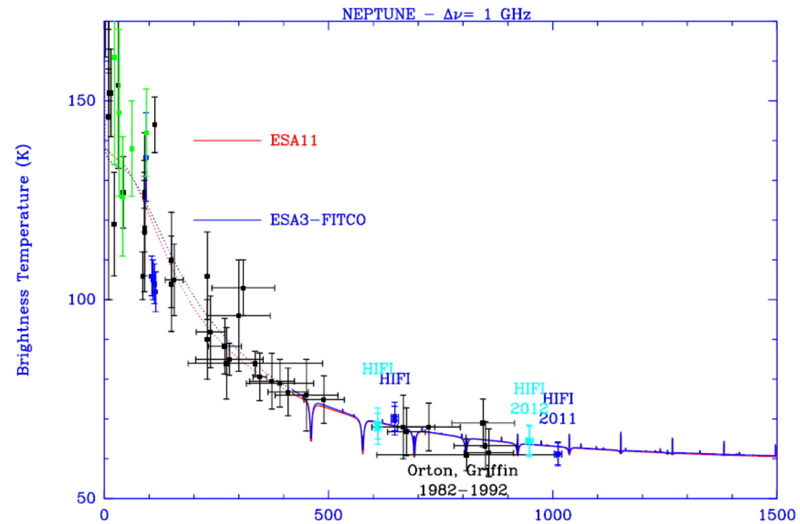
But some tweaking since HD 57 μm line fit is not great

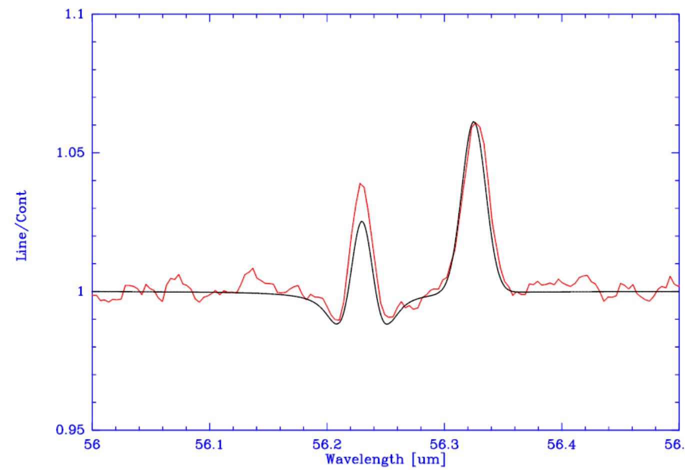
- Higher temperature in the stratosphere (as per Uranus?)

-Vary the Temperature contrast at Pressure between 0.1-2 Bar

-The pressure level threshold P0 seems more in the 1-10 mbar range

-Fit IRAM heterodynes observations of CO



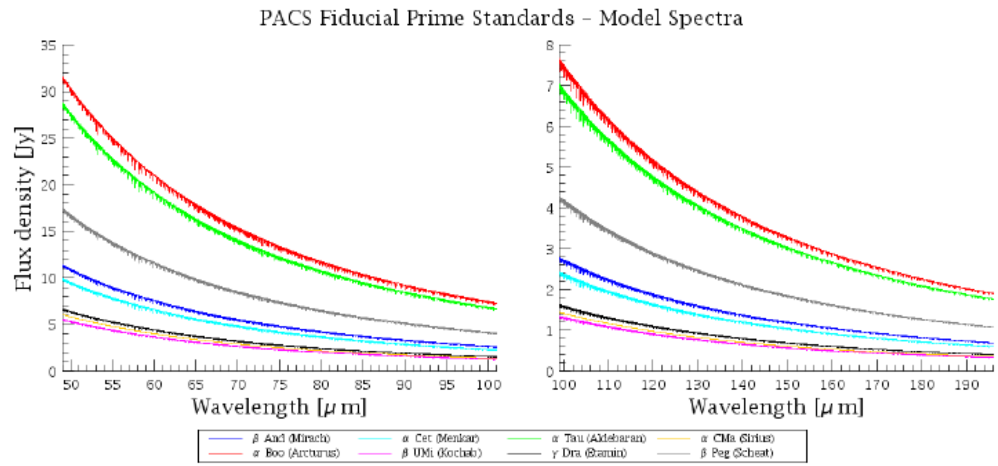


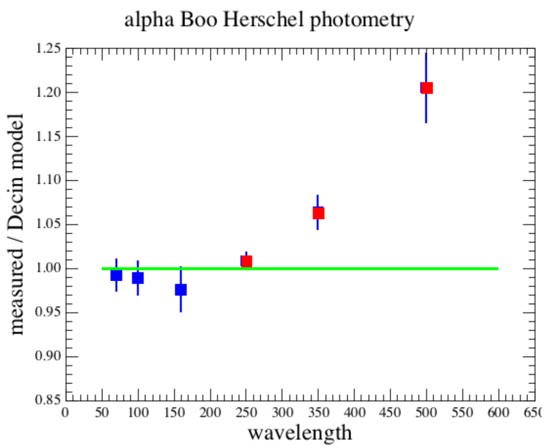
Closing comments

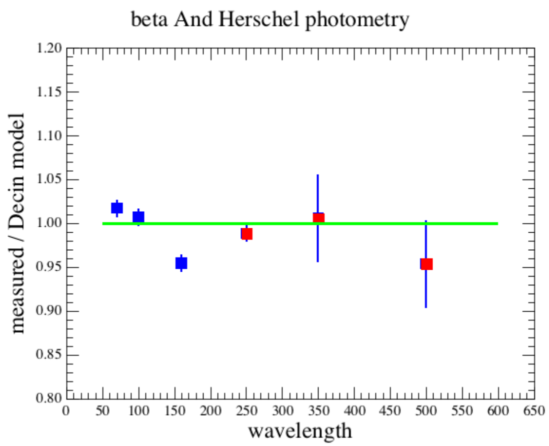
- Uranus and Neptune models are consistent with Lellouch et al Mars models – cross-calibration measurement by HIFI (1-2%).
- Uranus and Neptune consistent with each – 1-2%.
- Consistent with spectra of the telescope emission across the whole spectral range of SPIRE within a few percent.
- Consistency against stellar calibration (see later).

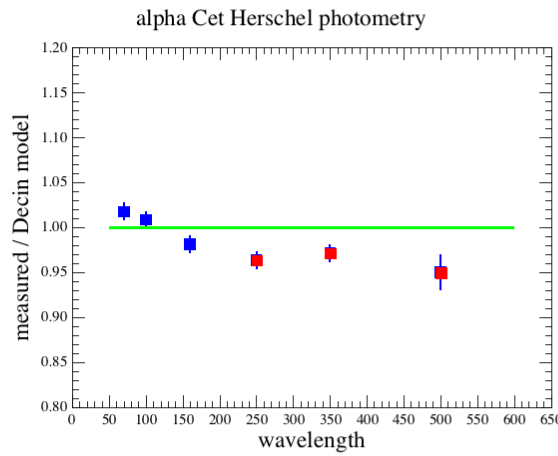
Stellar models

- Based on pre-launch stellar (MARCS) models of Leen Decin and collaborators (Dehaes et al, 2011; A&A, 533, 107).
- Atmospheric model calculations for stars. With accurate K-band photometry (Selby) providing absolute flux levels.
- Prime calibrators for PACS.
- Early data suggested some chromospheric emission – 8 → 5 stars.









Limits of the stellar models

- 2 M and 3 K stars.
  - α Boo K2 III
  - α Cet M2 III
  - α Tau K5 III
  - β And M0 III
  - γ Dra K5 III
- Uncertainty in models at launch indicated as 5%. But we need better…..
- One element now being considered is angular diameter at observed wavelength.
  - Likely 1 – 4% increase in fluxes for fiducial stars.
  - Interferometer measurements ??

  - **See presentation by Joris Blommaert**

Asteroid models

- Initial checks indicated that PACS/SPIRE fluxes (flux calibration based on planet/stellar models) were very close to as predicted by models.
- Based on the models of Thomas Müller (measured sizes, shape models, albedos). See Müller & Lagerros (2002; A&A, 381, 324)

SPIRE fluxes and errors

1 Ceres	13	13	36.60	1.00	1.01	1.00	0.03	0.02	0.03
4 Vesta	15	15	15.51	1.07	1.11	1.09	0.02	0.02	0.02
2 Pallas	9	9	10.45	1.09	1.10	1.10	0.03	0.03	0.03
10 Hygiea	6	6	7.64	1.03	1.01	1.02	0.04	0.11	0.09
3 Juno	9	9	5.89	0.99	0.96	0.95	0.03	0.03	0.03
52 Europa	6	6	4.58	1.02	1.02	1.03	0.03	0.03	0.02
7 Iris	2	2	4.27	0.88	0.88	0.86	0.11	0.12	0.14
6 Hebe	6	6	3.86	1.03	1.01	0.98	0.09	0.09	0.09
8 Flora	1	1	3.16	1.03	1.03	1.02			
704 Interamnia	3	3	2.29	0.95	1.00	1.01	0.18	0.10	0.06
29 Amphitrite	3	3	1.80	0.94	0.91	0.88	0.07	0.07	0.08
511 Davida	3	3	1.61	1.03	1.10	1.01	0.05	0.08	0.07
88 Thisbe	2	1	1.44	1.07	1.07	1.07	0.15	0.15	0.11
19 Fortuna	1	1	1.43	0.84	0.85	0.71			
65 Cybele	3	3	1.41	0.98	0.98	0.97	0.18	0.19	0.20
372 Palma	1	1	1.25	0.84	0.85	0.84			
173 Ino	2	2	1.12	0.75	0.75	0.78			
54 Alexandra	1	1	1.07	1.25	1.27	1.29	0.37	0.38	0.33
20 Massalia	1	1	0.74	0.98	1.00	1.05			
93 Minerva	2	2	0.55	0.91	0.91	0.94			
47 Aglaja	2	2	0.41	1.20	1.21	1.18	0.07	0.11	0.08
21 Lutetia	1	1	0.26	1.00	1.01	0.94	0.06	0.04	0.08
253 Mathhilde	1	1	0.25	1.26	1.31	1.41			
				1.01	1.02	1.01			

Excellent agreement as a group

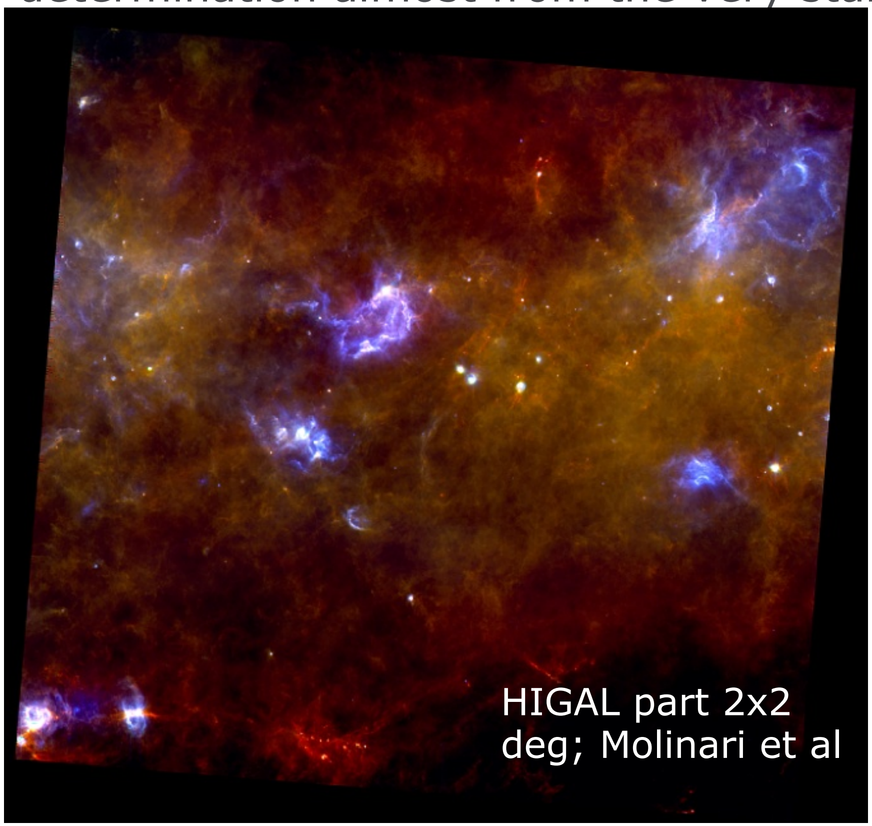
Limits on asteroid models

- Currently the best are now estimated as good to ~5%.
  - A handful as prime calibrators for FIR/Submm?
- A number of others have quality good enough for secondary calibrators of ~10% accuracy.
- Also useful for non-linearity characterization of PACS.
  - Range of fluxes available from asteroid calibrators – varying distances.
  - Non-linearity curve for PACS arrays well characterized
- Feedback of Herschel data to improve models further (up until recently not touched since launch).
  - Prime/secondary calibrator legacy from Herschel.

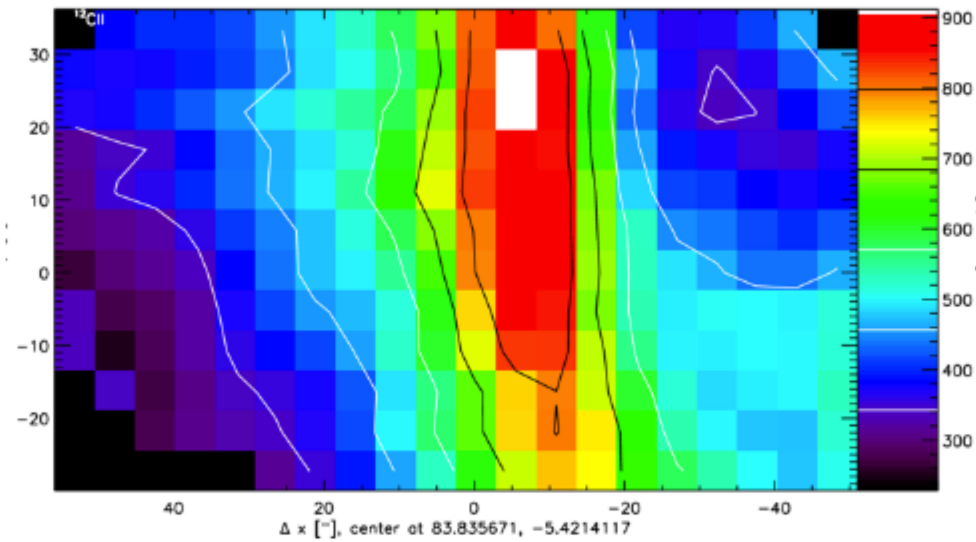
- See presentation by Thomas Müller.

Scan maps

- PACS and SPIRE photometers both use scan maps exclusively for all photometer science observations. HIFI uses OTF mapping for some measurements.
- Some spectacular images and point source fluxes extracted have been used for SED determination almost from the very start.



HIGAL part 2x2 deg; Molinari et al



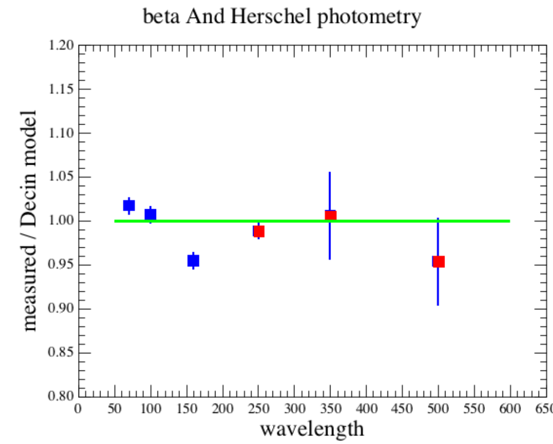
[CII] map of Orion bar using HIFI OTF mapping.

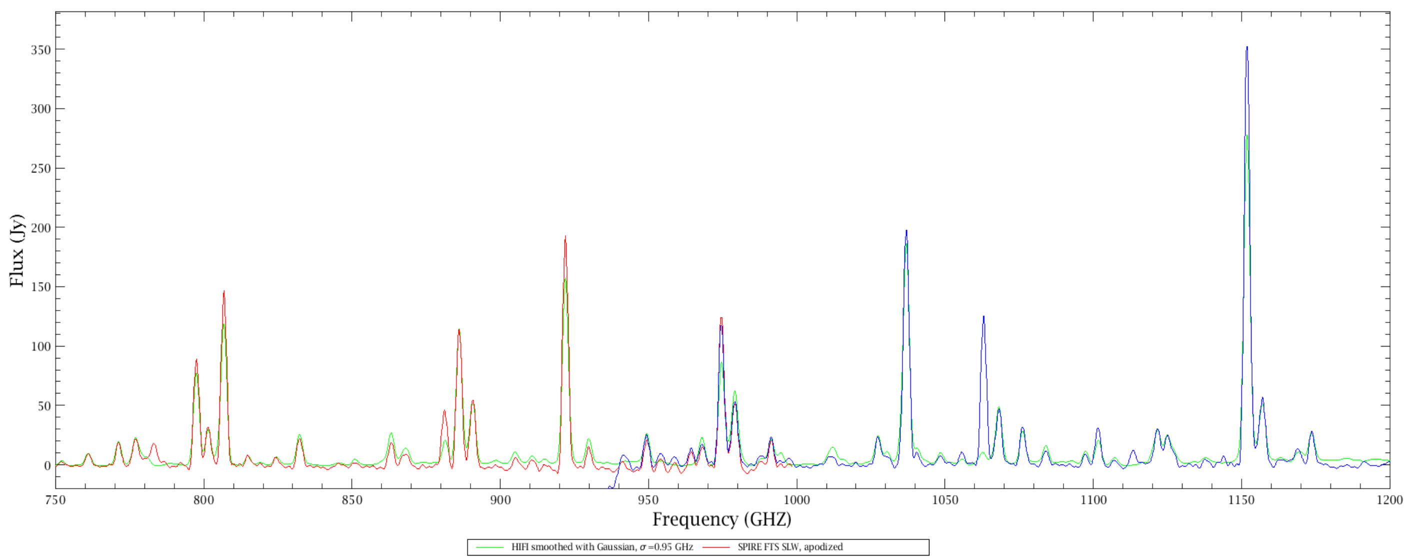
Mapping notes

- PSFs distorted by scans – depending on scan speed, notably for PACS.
- Beams recently measured in more details by all instruments
  - Original PACS-P beam not measured out far enough – extends over arc minutes
  - Recent deep SPIRE measurements have lead to improvements on beam knowledge and small increases on beam areas.
  - HIFI beams have now been precisely measured down to very low levels (see presentation by Willem Jellema).
  - Being fully incorporated (some already have) into pipelines/analysis software.
- But equally important has been the work on map making software in pipelines. All instrument have improved this capability over the mission. But ultimate/best?
- Map-making workshop was held at ESAC in January 2013. Some of the results and possible changes (?) for the future – see presentation by Roberta Paladini.
- **Deconvolution** of maps is well underway with various groups.

Cross-calibration between Herschel instruments

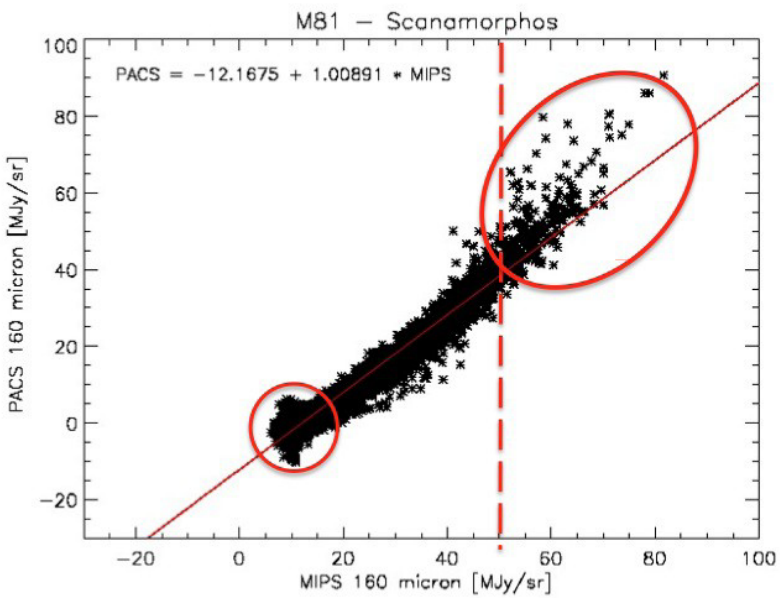
- Photometers seen earlier, e.g. Beta And. Linked via stellar models – remember SPIRE cal via Neptune!
- Program of measurements for spectrometer cross-calibrations has been completed.
  - Also helping with order overlap region of the longest wavelengths of the PACS spectrometer.
  - Understanding spectroscopy of small extended objects
  - See presentation by Elena Puga





Extended Emission

- Working group has been looking at SPIRE/Planck HFI cross-calibration this for some time.
  - Lead to some bootstrapping of elements of calibration on both sides.
  - Planck offsets used to correct SPIRE maps in standard HSC pipelines from HIPE 10 onwards.
  - See presentation by Bernhard Schulz
- PACS extended emission and comparisons to MIPS.
  - Long and tortuous history.
  - I consider it done with.



Spitzer/MIPS documented feature

MIPS Image Features and Caveats

http://irsa.ipac.caltech.edu/data/SPITZER/docs/mips/features

7. Flux Non-Linearities The flux nonlinearities for the MIPS-Ge detectors have yet to be fully quantified. These nonlinearities represent the differences in the flux conversion factor as a function of source flux. Currently, the SSC assumes a constant flux conversion factor for all flux ranges; see Table 4.10 in the MIPS Instrument Handbook. Early observations suggest that MIPS 70 micron sources (<100 few Jy) have flux non-linearities that are a <20% effect (see Gordon et al. 2005, PASP, 117, 503). The level of flux non-linearities for 160 micron has not yet been quantified, given the small number of asteroid calibration observations that have been carried out to date. Analysis is ongoing, and we will update this document as information becomes available.

When the long wavelength arrays of MIPS were designed using Ge:Ga, we had already half a century experience with this type of technology. The lessons learned from the Infrared Space Observatory (ISO) with the Photometer (ISOPHOT) and Long Wavelength Spectrometer (LWS) confirmed the superb sensitivity of this type of arrays, but also their susceptibility to a non-linear behavior under drastic (relative & absolute) changes of illumination, and in particular when highly energetic particles interact with these photoconductors. The MIPS non-linear behavior is already introduced in the "MIPS Instrument Handbook" under the "Detector Behavior subsection (2.2.3), and it is also briefly described in the 70 and 160 micron calibration papers by Gordon et al. 2007 (70um) and Stansberry et al. 2008 (160um), respectively.

Both MIPS Instrument and Instrument Support teams dedicated quite a bit of effort trying to correct the flux non-linear signal of the Ge:Ga arrays, but given that the data is calibrated in MJy/sr and that for point source science the signal was filtered, it was not possible to reach a unique solution. Recall that the data reduction pipeline for the Basic Calibrated Data (BCD) is identical for the Instrument Team and the Spitzer Science Center (by design), and so different approaches to correct the data have been followed at the Post-BCD level, i.e. on the final combined image.

The SSC Post-BCD products for the 70 and 160um mosaics are NOT corrected by flux non-linearity effects.

The MIPS IST prepared a document in 2009 on the 70um array flux non-linearity, using the fact that at 70um, one has the Wide Field, Narrow Field and SED modes that allowed to explore a large dynamic range on illumination using the same array. The report is based on the SSC Post-BCD products, the same products that currently populate the Spitzer Heritage Archive. This document is posted under the MIPS Papers & Technical Reports.

Pointing

- With strong calibration goals, pointing was always going to play an important role.
- Started with ~2” APE and 0.”3 RPE (jitter). But issues with…
  - Speed bumps – due to hot pixels → STR CCD temperature change.
  - After effective focal length changed → areas of sky where several arcseconds offsets
- After much effort – especially in the PACS ICC the effects of STR distortions have been mapped. Looking to include in next HIPE release.
  - Overall a posteriori pointing improvements
- But jitter also a large effect with PACS spectroscopic measurements particularly.
  - Reduce it? Looks likely
  - Make appropriate flux corrections for PACS-S
- See pointing session on Wednesday afternoon.

Conclusions

- What has been presented in the setting of the flux scales (particularly) by the work of the Herschel Calibration Steering Group.
  - Planet models give ~5% point source accuracies. Iteration is bringing this closer to 3%.
  - Stellar models being reassessed to include “smaller” effects. Expected to reach similar levels.
  - Asteroid models – a legacy from Herschel. Prime calibrators?

- Photometers give excellent repeatability on calibration targets. The limits to the flux calibration
  - Limit has become the uncertainty in the calibrators themselves rather than the instruments (<5%)
  - Extended emission has a somewhat higher uncertainty (beams/mappers used). Better beam measurements and work on mappers ongoing.

Conclusions II

- Spectrometers have higher uncertainties, not so much on the flux calibration but on the optimal extraction of spectra and corrections for effects such as spacecraft jitter (see presentation by Helmut Feuchtgruber), or HIFI sideband ratio (see presentation by Ronan Higgins).

- Frequency/wavelength calibration: for HIFI and SPIRE governed by physical/measurable mechanisms, e.g. local oscillator + comb.
    - Comparison to HIFI can indicate the accuracies of PACS/SPIRE lines measured absolutely (for spectral regions of overlap).