Gaia's potential for interpreting asteroids

Collaboration of Marco Delbo with Francesca DeMeo
with input from Paolo Tanga and Phillipe Bendjoya
January 2013

Purpose of Visit

The purpose of my visit was to determine the potential of Gaia to interpret asteroids based on the spectral data it will obtain. My purpose was also to discuss classification methods and philosophies so the resulting taxonomy will be as valuable as possible to the asteroid community. The work carried out during this collaboration included determining the spectral resolution throughout the entire resulting Gaia spectrum (BP + RP) and comparing that with the spectral resolution of previous taxonomies. I outline the work carried out and the results obtained below.

Summary

Gaia will observe about 400,000 asteroids. Here we look at the expected spectral resolution and signal-to-noise ratio of the Gaia blue-photometer (BP) and red-photometer (RP) data of asteroids and compare it with the spectral resolution used for the visible wavelength spectral taxonomy by Bobby Bus (Bus 1999, Bus & Binzel 2002). We find that the spectral resolution is comparable and sufficient to resolve weak features seen on asteroids, particularly important for the C and X taxonomic complexes. Finally, we convert spectra from DeMeo et al. (2009) to Gaia's resolution and do a simple spectral slope calculation to show how the broad taxonomic classes can be separated. A more detailed separation of different spectral characteristics including the weaker bands and features will require more sophisticated analysis. This analysis could include, for example, unsupervised classification, which is planned in the data treatment pipeline of the DPAC, or principal component analysis, which has been the basis for asteroid classification for three decades.

Introduction

We aim to address whether Gaia data will be capable of detecting spectral features identified in the Bus and Bus-DeMeo taxonomies. First we determine what the spectral resolution of the Gaia BP and RP data will be and create sample points that represent data at that resolution. Then we compare the spectral resolution of Gaia to the 49 channels used in the Bus taxonomy. We plot each of the major spectral classes to see the spectral variability of each class seen in the "Gaia" data. We focus particularly on an example of a minor feature, the 0.7 μm band indicative of hydrated minerals. Finally we perform a very simple parameterization of the Gaia data to show how the classes major classes separate.

Determining Spectral Resolution

We note first that the BP and RP CCDs have 4500 x 1966 pixels in the along-scan (AL) and across-scan (AC) directions, respectively; that the pixel size is 10 x 30 μm corresponding to 58.933 x 176.789 mas AL and AC respectively.
The spectral resolution $d\lambda$ is given by the the inverse of the derivative (wrt λ) of the dispersion function (κ). The latter relates the spatial coordinates to the wavelength $x = \kappa(\lambda)$.

$$d\lambda = dx \left(\frac{d\kappa}{d\lambda}\right)^{-1} \quad (1)$$

We assume that dx i.e. the spatial resolution element on the focal plane is given by the Rayleigh criterion of the width of the point-spread-function (PSF) in the AL direction.

$$dx = 1.22\lambda/Df \quad (2)$$

dx is about 9 μm at $\lambda = 0.3$ μm and 30 μm at $\lambda = 1.0$ μm, i.e. between 1 pixel and 3 pixels AL at the blue and red end of the spectral interval respectively.
We obtain κ from the Gaia Parameters Data Base. Note there is a function for each photometer, namely the following fits files:

```
:Satellite:BP:Spectrum_DispersionFunction
and
:Satellite:RP:Spectrum_DispersionFunction
```

Given the value of $d\lambda$ as a function of λ we define the spectral bins. The bins are constructed such that there is one with central wavelength at 0.55 μm. The BP and BP bins exend only in the regions where each photometer is reasonably sensitive (e.g. not beyond 680 nm for BP and not short of 650 nm for the RP). Figure 1 shows the values of $d\lambda(\lambda)$ for the BP and RP and the boundary of the spectral bins.

Comparison of Bus and Gaia spectral resolution

We take the center of the spectral bins constructed as detailed before and shown in Fig. 1. The plots of Figs. 2 and 3 show average spectra for two interesting broad asteroid spectroscopic classes, namely the A- and the Ch-class. In the appendix we give plots for all the broad asteroid spectral classes of Bus and DeMeo. The Bus datapoints are plotted in black. The black error bars represent one standard deviation variation within the class. The estimated Gaia points are plotted in red. The expected SNR for each Gaia datapoint for a single

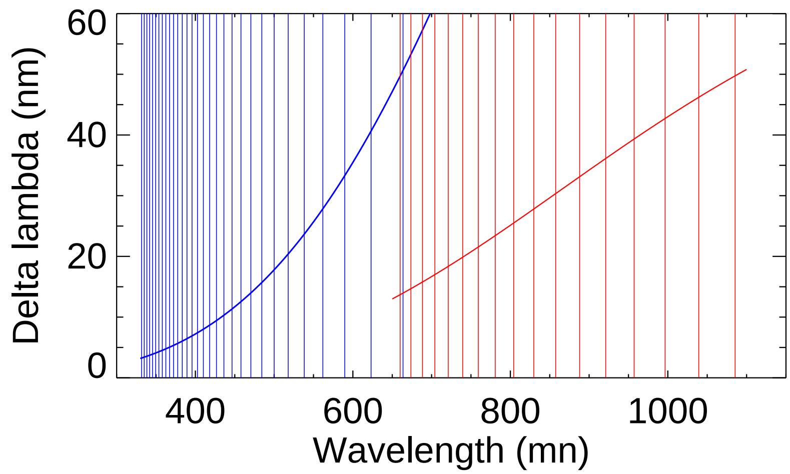

Figure 1: Curves are the spectral resolution of BP and RP, vertical lines denote the bins of spectral resolution. The bins are constructed such that there is one with central wavelength at 0.55 μm.

observation of a 17th magnitude object is shown as red error bars. The value of the SNR is calculated according to the procedure of Delbo et al. (2012) for each transit. Note that the average spectrum reflectance values plotted between 0.3-0.45 μm is fake data meant for illustrative purposes only (as the Bus and the Bus and DeMeo taxonomies do not have/use data shortward of 0.45 μm).

In Fig. 2 plot we can easily detect the broad and deep 1 μm feature of the A-type asteroid. The spectral resolution of the Gaia data is comparable with though slightly less than that used for the Bus taxonomy. In the figure 3 we see the Ch spectrum. The weak feature centered near 0.7μm has a depth of only a couple percent. Although there is sufficient spectral resolution to resolve this band, a high signal-to-noise ratio is required.

We created plots for each broad compositional class. The Bus and Gaia data are compared and the signal-to-noise for a single observation of an object are plotted for a sense of the quality of the data. We do not include these plots in this report because of the length limit.

We then performed a simple parameterization of the data similar to the fashion done for SDSS data. We calculate the slope of the data between 0.45-0.75 μm and between 0.75-1.0 μm as a rough proxy for the continuum slope and band depth. The spectra used were the $\sim$370 objects used in the Bus-DeMeo taxonomy converted to Gaia data points. The figure shows how many of the major classes can be separated.

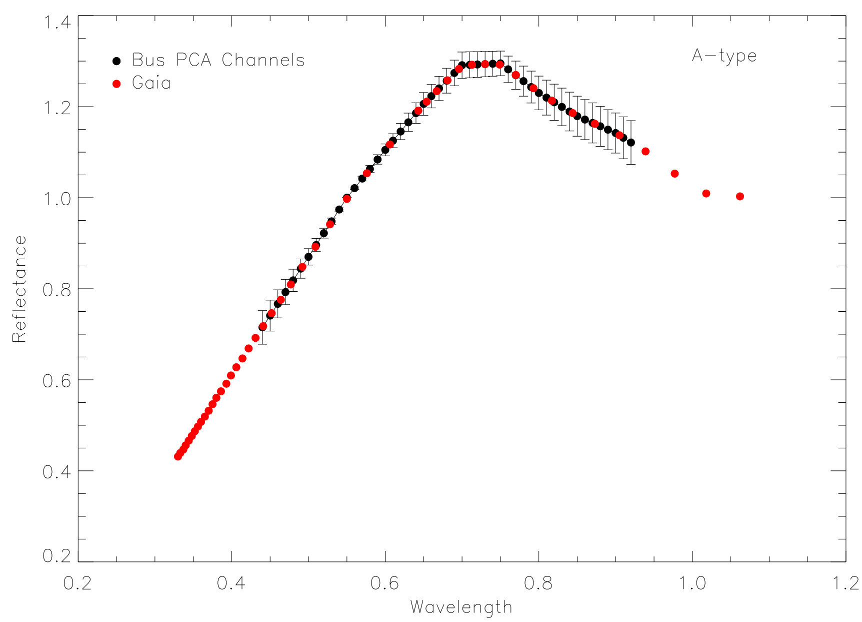

Figure 2: Plot of a typical spectrum of an A-type asteroid. The spectral resolution of the Gaia data is comparable to that of Bus.

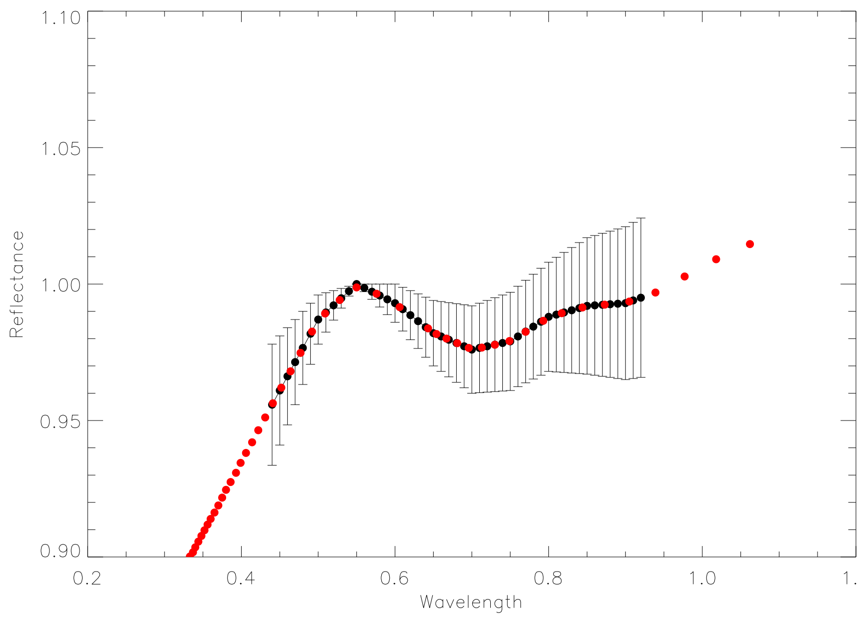

Figure 3: Plot of a typical spectrum of an Ch-type asteroid. While there is sufficient spectral resolution to detect the 0.7μm band, a high SNR will be necessary to detect such a weak feature.

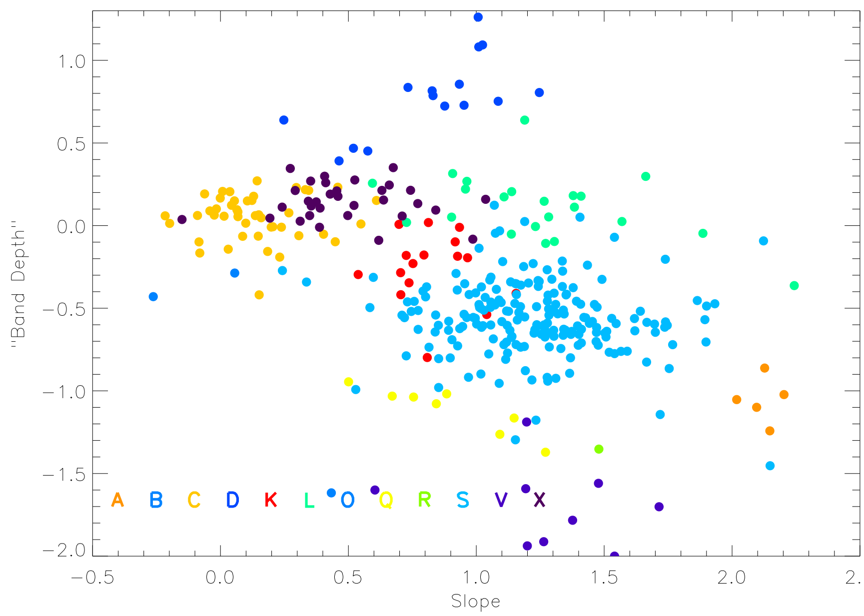

Figure 4: Separation of the classes for "Gaia-like" data based on two simple parameters. The x axis is the slope between 0.45-0.75μm the y axis is a simple proxy for band depth measured as the slope between 0.75-1.0μm. We can clearly see the separation of many of the major classes. To resolve the finer features and more detailed classes, a more sophisticated mathematical tool will be necessary.

Capability of Gaia data

Here are a handful of observations based on this dataset we will be able to achieve the following:

- If the signal to noise is good enough between 0.95-1.2 μm we will be able to distinguish between true A-types and S-types that have A-like spectra in the visible range.
- The weak bands in the visible will need high SNR for confident detection. Multiple observations/transits will be necessary.
- Binning the 0.3-0.4 μm region down to a couple points to increase the SNR will likely provide valuable information about the slope in that region.
- Because V-types have a band minimum at short wavelengths the band minimum should be detectable. It might be possible to perform basic mineralogy of V-types based on band min and band depth.

Conclusions

We find that the spectral resolution is comparable though slightly less than the resolution for Bus and sufficient to resolve weak features seen on asteroids, particularly important for the C and X taxonomic complexes. We have summarized the capabilities of the Gaia data to characterize many important asteroid features and will span a wavelength range and spectral resolution not covered by any single spectral survey to date.

Future work to perform is to determine how many observations of a single asteroid are necessary to have sufficient SNR to detect weak bands based on the expected SNR for a given magnitude for a single observation. Signal-to-noise can also be increased by binning the data while still maintaining enough spectral resolution. Binning may be needed at the short and long wavelength ends (0.3-0.4 and 1.1-1.3 μm) because of the low efficiency of the detector at those wavelengths. Additional work and preparation should include comparison of the unsupervised classification versus established taxonomies. It could also be useful to take the three established taxonomies (Tholen, Bus, and Bus-DeMeo) and determine what groupings we might expect from Gaia because the Gaia data will cover a wavelength range and spectral resolution that no single existing taxonomy has addressed.