Heat Flux Constraints from Variance Spectra of Pluto and Charon from Limb Profile Topography

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Key Points:
• We derived new limb profile topography datasets of Pluto and Charon based on the body edge in images.
• For Charon, the topographic variance spectrum displays a distinct change in slope at ~150 km wavelength.
• Charon’s topography records high heat fluxes from either tidal heating or a giant impact.

Abstract
We derive a topography dataset from images of Pluto and Charon that contain the body edge (i.e. limb profiles) which will help in understanding the comparative history of the binary system. We use the profiles to derive topographic variance spectra and find that while the variance spectrum of Pluto fits a single power law, Charon’s spectrum displays a clear breakpoint at ~150 km wavelength. Assuming the breakpoint is a result of topographic flexure, we find that Charon’s elastic thickness must have been 20±10 km during topography formation. A lack of a breakpoint for Pluto sets a minimum elastic thickness for Pluto of 60 km. We use these elastic thickness estimates to calculate a maximum heat flux of ~13 mWm⁻² on Pluto during and after topography formation. On Charon, however, we find that the heat flux during topography formation was 35±14 mWm⁻². This range of values far exceeds the likely radiogenic heat production and is consistent with either heat released following the Charon-forming impact event or (more likely) tidal heating during Charon’s early history.

Plain Language Summary
Studying the topography of planetary bodies provides key insights into the geologic processes of their surfaces and interiors. In this work we develop a topography dataset for Pluto and Charon by mapping variations in the height along the worlds’ edges in images from New Horizons. We analyze the data to determine roughness using the mean amplitude of mountains and valleys for a range of widths. Pluto shows the expected result of a single slope decreasing in roughness at shorter widths, but Charon has a change in the slope at ~150 kilometers. Mountains and valleys on Charon wider than this are respectively shorter and shallower than expected. This gives
insight into how the landforms on Charon formed as well as the ability of Charon’s crust to support variations in elevation. Charon’s landforms must have formed at the observed size or decreased over time to have modern amplitudes. Either case implies that Charon had a thinner ice shell, and was relatively hotter, than Pluto in the ancient past. This extra heat is consistent with a Charon-forming impact or (more likely) tidal heating during the Charon’s initial history.

1 Introduction

When the New Horizons spacecraft reached the Pluto system in 2015, the illuminated disks of Pluto and Charon revealed the complexities of these Kuiper Belt Objects’ geologic histories (Stern et al., 2015). Pluto is a world with a surprising range of surface ages and processes (Moore et al., 2016), while Charon has experienced a large amount of tectonic deformation (Beyer et al., 2017). Understanding why this difference in surface expression has resulted from the evolution of the Pluto system is one way to understand Kuiper Belt objects in general. We use topography derived from the body edge (i.e. limb profiles) in images of Pluto and Charon to study if there is an observable difference in the topographic variance of the two worlds.

While the current understanding of Pluto and Charon is based primarily on studies following the New Horizons spacecraft mission, we will use ideas and techniques used in studies of other icy bodies. Although there are likely geologic differences between the two types of worlds (icy dwarf planets and icy satellites) due to how they form (Bierson and Nimmo, 2020), their water ice crusts are likely to have similar rheologies. As a result, we will make use of previous studies that focus on understanding icy satellites with limb profiles (e.g. Nimmo et al., 2011).

We analyze the shapes of Pluto and Charon to understand the internal, thermal, and surface history of the two worlds. Nimmo et al. (2017) started this analysis of Pluto and Charon, focusing on the global shape (i.e. degree-2) using topography obtained from limb profiles. They found that both Pluto and Charon have flattening values less than ~0.5%, which makes them effectively spherical. This puts broad constraints on the internal evolution of Pluto and Charon, and this lack of a fossil bulge is part of the argument for the existence of a past (and possibly present) subsurface ocean for both bodies (e.g. Keane et al., 2016; Nimmo et al., 2016).

However, the limb profiles from Nimmo et al. (2017) contain information over a wide range of wavelengths. By expanding upon their work, we can investigate aspects of Pluto and Charon over a range of wavelengths. This increased range in wavelength analysis is one way of investigating if Pluto and/or Charon have been heated beyond radiogenic heating.

Length scales intermediate between those considered to represent the shape of the body (e.g. the flattening) and individual surface features contain geologic information about the interplay between interior and surface processes (Shepard et al., 2001) and have been useful in determining geologic parameters, especially the thickness of a crust’s elastic layer (e.g. Araki et al. 2009, Nimmo et al., 2011). We analyze our limb profile topography dataset using Fourier analysis to understand how the amplitude of the topography varies over a range of wavelengths. With this analysis, we find that the amplitude trend as a function of wavelength of Charon’s limb profile topography has a break (i.e. change) in slope at a length scale in the range of ~70-300 km. This observed characteristic wavelength for Charon’s topography implies that either a surface process (or processes) prefer to form features at that wavelength or the interior behavior of the
crust changes at a related wavelength. We analyze our results assuming that the latter is the case as it is not clear why a surface process would form features preferentially at that wavelength on Charon, while not doing so on Pluto. More specifically, we assume that the characteristic wavelength is the flexural parameter, implying an elastic thickness of ~20±10 km. We also derive a minimum elastic layer thickness of 60 km for Pluto from a lack of break in slope. The thickness of these layers can be used to constrain the total conductive ice shell thickness and the surface heat flux at the time of topography formation. Compared to previous studies (Conrad et al., 2019), we find surface heat flux values for Pluto (~13 mWm⁻²) that are more consistent with a primarily radiogenic heat source. However, the values for Charon (35±44 mWm⁻² during topography formation) require additional heat sources, which could be sourced from tidal deformation or a Charon-forming impact.

2 Methods

The primary goal of this study is to produce topographic datasets for Pluto and Charon derived from planetary limb profiles, separate from photogrammetry-derived digital elevation models (DEM; Schenk et al., 2018a and 2018b). We achieve this by determining the edge of the planetary body from images (i.e. limb picks). Using map projections and the known observing geometry, we can transform the pixel locations of the limb picks into a list of elevations at specific latitude and longitude locations. While our methodology mostly matches that of Nimmo et al. (2017), we will reiterate some aspects of their methods to detail updates and changes.

2.1 Limb picking methods

We began our process with a survey of New Horizons images from the Long-Range Reconnaissance Imager (LORRI; Cheng et al., 2008) and the Ralph instrument’s Multispectral Visible Imaging Camera (MVIC; Reuter et al., 2008) sub-instrument. Data from both instruments have been used extensively to study Pluto, Charon, and most recently Arrokoth (Spencer et al., 2020). Starting with the Planetary Data System, we surveyed the images to create a list of images containing body edges starting when Pluto was ~100 pixels in diameter. In addition, we removed redundant images from the list. This list contained both day-side and night-side images from both LORRI and MVIC as the starting point for further analysis.

While we initially performed limb picks and fits for both LORRI and MVIC images, we found large-amplitude, long-wavelength undulations for MVIC limb profiles. This occurs in MVIC images due to the line-scan exposure method combined with spacecraft motion (Weaver et al., 2009). Due to the relatively small number of MVIC images, we instead focus on the LORRI images in this analysis.

For limb picks of day-side (i.e. front-lit) images, we use Method A as presented in Nimmo et al. (2017). This method scans each row and column in the image to find the location of the limb where the brightness along the scan compared to the brightness of the on-body profile reaches a specific threshold. They found that two of their three methods (A and B) did not have systematic issues in over or under-estimating the radius, based on synthetic Pluto images. This is because the parameters in those methods could be tuned to correct the estimations. We generally calculate the average brightness over the same distance range (0.5d to 0.9d, where d is the on-
body profile length from center to body edge) and then use the same brightness threshold (40%) as Nimmo et al. (2017) used with Method A. Images that show initial limb picks can be seen in Figure 1 of Nimmo et al. (2017).

Once the list of limb pixel locations is determined, we visually verify the algorithmically chosen limb picks and manually remove picks that are obviously not on the limb. These false limb points are often the result of either albedo variations or the terminator. Large albedo variations are only an issue with Pluto images that contain Cthulhu Regio\(^1\) (CR), a region south-west of Sputnik Planitia (SP). Limb picks of images that contain areas of CR that border regions of high albedo (e.g. SP) tend to place the limb location in CR inward of the actual limb. This happens because the average disk brightness is incorporated into the algorithm, and if the brightest area of Pluto is near the middle while the darkest is at the edge, the 40% cutoff will occur before the actual limb location. However, we note that the local albedo at the limb does not show a systematic correlation with topography (see section 3.1), suggesting that this effect is minor. The algorithm also does not discriminate between the limb and terminator of the body, and we only use locations where the edge of the lighted hemisphere is caused by the edge of the body (limb) rather than the edge of the illuminated hemisphere (terminator). While some terminator picks can be accidentally incorporated into a set of limb picks, we apply additional geometric checks in the fitting method described below to remove points not located on the illuminated limb.

Although Nimmo et al. (2017) provide an extensive discussion of the uncertainty in recovering a body's radius, they did not discuss the uncertainties associated with individual limb picks. Dermott and Thomas (1988) argue that the limb location (a sharp transition in brightness) can be located to within ~0.2 pixels. Since our method is similar to theirs, we assume that the same level of uncertainty applies to our limb profiles.

In night-side (i.e. backlit) images, the disk of Pluto is weakly illuminated by forward-scattered light from atmospheric hazes. The sharp contrast between the dark disk and the bright haze is captured very clearly by taking the gradient of the image. Therefore, to identify the limb in backlit images each row and column of the image is scanned away from the body center and the limb is taken to be the location of the maximum gradient. Unfortunately, this technique does not work on Charon due to its lack of atmospheric hazes. Additionally, while this technique produces good quality topography for middle to long-length scale features (~100 km; see Stern et al., 2020 for an application of night-side derived topography), at short wavelengths the profiles are noisy, presumably due to the low signal-to-noise ratio. Due to contamination concerns in our spectral analysis, we therefore focus on front-lit LORRI images in the following sections.

2.2 Limb fitting methods

After determining the limb location in terms of pixels \((x, y)\), we use the camera intrinsics in the SPICE instrument kernels to project these points onto a spherical body to convert to an equivalent latitude, longitude position \((\phi, \theta)\) on a spherical body given the image coordinates of the body’s center \((x_0, y_0)\), the latitude and longitude of the sub-spacecraft location \((\phi_0, \theta_0)\), the body’s radius \(R\) and the orientation of the rotation pole relative to the image \((\phi)\). The spacecraft

\(^1\) Some names on Pluto and Charon are now formalized and others are still informal and follow the informal names in Moore et al. (2016).
parameters are calculated using the most consistent SPICE information based on the smithed kernels from Schenk et al. (2018a&b). We report these values for all used images in Supplementary Tables 1 and 2, and the results of the pixel locations for $x_0$, $y_0$ and $R$ (in pixels) in Supplementary Tables 3 and 4. We use a general vertical perspective (GVP) projection for determining the latitude, longitude positions ($\phi$, $\theta$) of limb pick locations (Snyder, 1987). Near closest approach, we account for the effect that can lead to a shifting of the limb to an angle less than $90^\circ$ away from the sub-spacecraft point. At distances $d$ far from the body center ($d >> R$), the GVP projection reduces to the orthographic projection, which is commonly used in limb profile fitting studies (Nimmo et al., 2017). In our projections we assume that both Pluto and Charon are spherical, based on the results of Nimmo et al. (2017). This simplifies the map projection calculations and determination of the radii from the (x,y) pixel locations. We also check if points are on the limb rather than the terminator by determining the angular separation between the points and the subsolar point on the surface. If the angle between the two points is greater than $90^\circ$, we remove the point from the limb profile. Subsolar coordinates are also present in Supplementary Tables 1 and 2. Elevation is reported as relative to the mean radius of Pluto (1188.3 km) and Charon (606 km) also determined in Nimmo et al. (2017).
Figure 1. Maps of Pluto (a) and Charon (b) with limb profile locations and topography. Labels number specific limbs to the indexing in Figure 3, and limbs are generally arranged in the encounter sequence from right to left. Other labels reference major areas on both bodies. Sputnik Planitia (SP), Cthulhu Regio (CR), and Pluto’s Far Side (PFS) for Pluto. Vulcan Planitia (VP) and the Charon Far Side (CFS) for Charon. Background images are LORRI/MVIC mosaics (Moore et al., 2016) centered on the anti-encounter hemispheres of Pluto and Charon. Coordinate systems are constructed such that the zero latitude, zero longitude are placed on the Pluto-Charon
tidal axis with longitude increasing eastward. Elevation color bars are capped at ±8 km to best show variations near mean elevations.

As expected from the flyby timing relative to Pluto’s rotation rate, we managed to obtain wide longitudinal coverage from the images. The longitudinal range spans about 220° on both worlds. While the coverage is not enough to perform analysis of global shape beyond degree 2 (e.g. see Nimmo et al., 2017) using spherical harmonics, the profiles cross a wide range of terrain types. Although these profiles may be used to study individual features, in this manuscript we focus on the variation of roughness with wavelength contained within the profiles. The image properties and limb picking information relevant to our analysis are included in Supplementary Tables 1 (Pluto) and 2 (Charon) in the appendix.

2.3 Data processing methods

After we obtain raw limb profile topography, the data are processed to remove a few different possible problems as described below. Generally, we use the raw data for most of our analysis, while the processed data is used with presentation of limb profiles and some aspects of our analysis. We note when we use the processed data in the relevant sections. Our primary post-processing concerns are long-wavelength false signals and short-wavelength noise. Since LORRI is a framing camera, any long-wavelength signals with LORRI images are likely real. For the presentation of the profiles in Figures 2 and 3, however, we detrend the profiles by removing the linear trend through the endpoints of the profile after interpolation (see below). This matches part of the processing we use to perform Fourier transformations in section 3.2.
Figure 2. A comparison of Pluto and Charon limb profiles at similar distances from the two bodies. At a distance of ~400 Pluto Radii (~2.25 km/pix ground sample distance), with a vertical exaggeration of ~132, these show how the topography at different scales vary between the two worlds. Labels to the left of the profiles corresponds to the labels on Figure 3, and the profiles are offset by 5 km. The dots plot the raw data before interpolation and detrending. A pixel scale bar is included to show how images translate to our limb profile topography. The 0.2 pixel corresponds to the uncertainty that Dermott and Thomas (1988) found with their similar method. Note the differences in roughness at long and short wavelengths. Charon has notable highs and lows at long wavelengths, but Pluto is rougher at shorter wavelengths.

Figure 2 compares our raw limb profile picks with the processed version. The short wavelength noise occurs due to the methodology of our limb picking algorithm. When we apply the line-scan
method, the algorithm scans both vertically and horizontally. This can introduce noise when the horizontal and vertical scans to pick the limb yield a different answer for the same point, and usually occurs in areas of varying brightness around the limb (this can be observed in the left-hand side of the Charon profile in Figure 2). To remove the shorter wavelength noise, as well as prepare our limb profiles for further analysis, we interpolate the limb topography onto a grid with constant spacing at a slightly worse ground sampling distance (half the total number of original data points). We use a gaussian weighted interpolation technique which allows us to control the scale that weighs the input values for each location:

\[ y'_j = \frac{\sum_{i=1}^{N} y_i \exp\left(-\frac{1}{2} \left(\frac{x'_j-x_i}{\omega}\right)^2\right)}{\sum_{i=1}^{N} \exp\left(-\frac{1}{2} \left(\frac{x'_j-x_i}{\omega}\right)^2\right)} \]  

Here the new \( j^{th} \) \((x', y')\) location is the point we’re interpolating from the original \((x, y)\) data, \( N \) is the number of points in the raw profile, \( i \) is the index over which we set the weighting from the raw data, and \( \omega \) is the weighting length scale. This length scale, individually determined on each profile, is set equal to half the median spacing of points in the raw profile. The median spacing is as high as 4.7 km at the chronological beginning of the set (limb P1) and reaches a minimum of 455 m for P22 and 346 m for C11. As Figure 2 shows, this successfully removes the scan noise.

![Figure 3](image-url). Stacked Processed (Detrended and Filtered) Limb Profiles for Pluto (a) and Charon (b). The vertical exaggeration for both figures is ~16. Limbs are labeled in the same manner as in Supplementary Tables 1 (Pluto) and 2 (Charon). Limbs are positive right-hand oriented, with the “western” edge on the left of the panel.

3 Analysis
A validation method we could use is a comparison between our limb profile-derived topography with the digital elevation model (DEM) of Pluto calculated using sets of stereo image pairs (Schenk et al., 2018a and 2018b). An unfortunate issue that arises due to New Horizons’ single fly-by is a mismatch between the coverage of our limb profile topography dataset and the DEMs. When our limb profiles have a comparable ground sample distance (~1 km per point) as the best areas of the DEMs (~300 m/pixel), they do not significantly overlap with those DEMs. At locations where we have limb profiles which do overlap with the DEM (e.g. P1-10 and C1-4), the low quality in both the DEMs and the limb profiles makes any comparison between the two (which would provide a useful cross-check) almost meaningless. The number of limb profile points in each of the two regions that we consider contain good short wavelength information (i.e. P6-10 and C1-4) only comprises ~4% of the total. All that can be stated with any confidence is that in the region where the DEMs and limb profiles overlap, for Charon the total relief measured by the two approaches is very comparable, whereas for Pluto the DEM-derived relief is a factor of 5 smaller than the limb-profile relief. We accordingly place more emphasis in the rest of this paper on our Charon results; further investigation of the apparent difference between the two Pluto data sets is desirable but not attempted here.

Another dataset for comparison is albedo values (Buratti et al., 2017). Since our limb picking method relies on the change in brightness, we need to investigate whether albedo variations are introducing biases into our limb picks. While Charon exhibits small albedo variations, we are more concerned with Pluto. This is due to the wide albedo variation observed on Pluto (Buratti et al., 2017), which can produce underestimates of the radius in scans that include both dark regions like CR and bright areas like SP. To investigate whether low-albedo regions (e.g. Cthulhu Regio) exhibit systematically low elevations, we took the Bond albedo dataset from Buratti et al. (2017) and interpolated the Bond albedo onto the limb profile coordinates. The Bond albedo maps are corrected for the body geometry in images and are thus mapped as normal reflectance scaled by a body-wide phase integral. Since the angle between the spacecraft look direction and the local normal is the same for all points on the limb, we assume that geometric effects are minor. The results can be found in Figure 4. We then found the best linear fit between the elevation and bond albedo and found that the correlation is weak ($R \sim 0.03$). Effectively there is no correlation between local Bond albedo and limb profile topography when considering the dataset as a whole; this suggests that any biases introduced by albedo variations are minor.
Figure 4. Correlation of Bond albedo and limb profile elevation for Pluto. Linear fit is plotted in red. There is no correlation between the two parameters (R ~ 0.03).

3.2 Topographic variance spectra

Topography generated from limb profiles can be used to analyze the long-wavelength properties of worlds. Limb topography variance spectra are a useful way of quantifying roughness as a function of wavelength (Araki et al., 2009; Shepard et al., 2001; Nimmo et al., 2011; Ermakov et al., 2018). To obtain the average variance spectrum, we calculate the discrete Fourier transform for each limb profile and then find the mean variance in a sequence of bins. For a set of evenly spaced topographic observations $h_i$, the discrete Fourier transform is (Press, 1992):

$$H_j = \sum_{i=0}^{N-1} h_i e^{\frac{2\pi i (j-1)}{N}}$$  \hspace{1cm} (2)

where $i, j$ are integers, $N$ is the number of values in the limb profile and the wave number $k$ associated with $H_j$ is given by $k = 2\pi (j-1)/L$, where $L$ is the total length of the topographic profile. We use the processed profiles which have been interpolated to a constant spacing and detrended. With the results for $H_j$, we then calculate the variance at each wave number as $|H_j|^2/N^2$. The results for both bodies are shown in Figure 5.
Figure 5. Pluto and Charon’s topographic variance spectra based on limb profile topography. a. Pluto’s topographic variance spectrum with a linear fit (red) and broken fit (cyan; Main et al., 1999). The variance results for the 22 Pluto limb profiles are put into 30 bins. The points represent the mean value in each bin and the shading equals the standard deviation. Pluto’s topographic variance spectrum is consistent with the expected single power law fit with a power law slope of \(~-1.8\). The improvement due to a broken slope is minimal, especially compared to the results of Charon. b. Charon’s topographic variance spectrum with a linear fit (red) and broken fit (cyan). The variance results for the 11 Charon limb profiles are put into 30 bins. Charon’s topographic variance spectrum is somewhat consistent with a single power law slope of \(-2\), but it is improved by adding a break in the slope at a wavelength \(~150\) km.

The primary result for both bodies is that they display a general power law trend with a slope of \(~-2\). However, on closer inspection a single power law does not hold particularly well for Charon at longer wavelengths.

Due to possible biases from the number/distribution of the limb profiles and the fact that limb profiles are inherently biased towards topographic highs, we verified our ability to recover an accurate power spectrum using synthetic data. The base synthetic data was generated using SHTools (Wieczorek and Meschede, 2018) with an input variance spectrum that resembles that of Charon, but with either a single \(-2\)-power law slope or the same with a flat variance spectrum before a break to a \(-2\)-power law slope at \(~150\) km (spherical harmonic degree 25). From the global synthetic topography, we sample by interpolating onto the same \((\phi, \theta)\) locations as our Pluto and Charon profiles. We found that we could identify a break in slope if it existed, although the slope recovered from the 1-D synthetic limb profiles was slightly higher than the input slope from the 2-D spherical harmonics (a difference in slope is expected). We also tested the effect of using apparent limb profile topography rather than the actual synthetic limb topography by using the technique outlined in Nimmo et al. (2010) for profiles that have similar chord lengths as our 11 Charon limb profiles. Using Nimmo et al. (2010)’s equation (2), we determined when the masking effect of high topography off the limb causes the apparent limb
topography to exceed the actual synthetic topography. We found that the variance spectra of the actual and limb-profile derived synthetic topography are essentially the same at long wavelengths and preserve the same break in slope. We conclude, as did Nimmo et al. (2010), that limb biases do not affect the variance spectra in any significant way at the wavelengths of interest. Comparison of our results with other efforts to find the variance spectra of Pluto and Charon (Ermakov et al., 2018) is deferred to the discussion section (section 4.2).

Determining the location and statistical strength of a possible break in slope/changepoint can be done using the method outlined in Main et al. (1999). We use their method to calculate the maximum Bayesian information criteria (BIC) with a set of possible changepoints (set at the middle of every bin), starting and ending at the fourth bin from each end. We calculate the linear fit on each side of the changepoint and compared our results to that found for a single slope linear fit. For both bodies, adding a break in slope tends to increase the fit across the spectra, as expected (Figure 6). However, while for Pluto the improvement in BIC compared to the linear fit, referred to as ΔBIC, is modest (<2), for Charon the ΔBIC=14. This implies a statistically significant improvement (i.e. ΔBIC>10; Kass and Raftery, 1995) signifying very strong evidence for an existence of a break in slope in the wavelength range ~70-300 km.
Figure 6. Change in the Bayesian Information Criteria from the linear fit. Hued lines are for Pluto (green) and Charon (magenta). After determining the BIC for the range of changepoints, we additionally determined the BIC for the linear fit. We consider the linear fit to be the null result, as a single power law slope is the commonly used approximation for the distribution of a solid world’s topography and requires the fewest assumptions. To compare Pluto and Charon, we subtract out the linear BIC to calculate the ΔBIC. While the peak for Pluto’s curve has some statistical strength (ΔBIC > 2; Kass and Raftery, 1995), Charon has a stronger fit over all changepoints. The wavelength range of 70-300 km for Charon is especially significant (ΔBIC > 10).

While a break in slope of the variance spectrum is sometimes seen for solid solar system bodies (Araki et al., 2009; Nimmo et al., 2011; Fu et al., 2017), there is probably more than one process which can create this break in slope. The break in slope in the Moon’s topography spectrum is
likely due to flexural effects (Araki et al., 2009), while on Ceres a crustal viscosity which varies with depth might be the cause (Fu et al., 2017). Pluto’s lack of an obvious break in slope may simply be the result of a rigid lithosphere. Given previous studies which provide a lower bound on Pluto’s elastic layer of ~10 km (Conrad et al., 2019), in the following sections, we test if the break in slope on Charon and the lack of a break on Pluto can be explained by elastic (flexural) processes.

3.3 Topographic support

Pluto and Charon’s modern crusts are the result of their evolution from the initial states they had after formation. Thermal models (e.g. Hammond et al., 2016; Bierson et al., 2018) show that the initial state has little effect on the current thickness of the ice shell: Pluto likely has a subsurface ocean and Charon should be completely frozen. However, while the mean final state of either body should be similar regardless of the initial state, the tectonic path they took depends on that state. The tectonic path refers to the duration and extent of strain in the ice shell. For both bodies there is extensive extensional tectonics (Moore et al., 2016; Beyer et al., 2017) on the order of ~1% areal strain (less on Pluto than Charon). But the strain rate and how that strain rate changes depends on the initial state of the ice shell (thick or thin), chemistry in the subsurface ocean, or large impact events (e.g. Sputnik Planitia) to name some processes.

As we noted in the previous section, a break in the topographic variance spectrum may signal some change in the ability of the body’s crust to support topography. As a rough approximation, this characteristic wavelength can be interpreted as the flexural parameter (Turcotte and Schubert, 2014). From the inferred wavelength range of 70-300 km for Charon, the implied elastic layer thickness is ~15±10 km at the time of topography generation. To derive this number, we use the parameter values in Table 1. We note that the modern thickness of Charon’s elastic layer is probably much greater as internal heating from radioactive material falls off with time (Nimmo and McKinnon, 2020).

To produce a slightly more precise estimate, we can instead specify an initial topographic roughness spectrum based on the short-wavelength slope. We then treat this initial roughness as a surface load and calculate the flexural deflection at each wavelength to determine the final topographic roughness profile. The flexural deflection is calculated using either Cartesian or spherical (Turcotte et al. 1981) assumptions; this approach is identical to that used in Nimmo et al. (2011).

In detail, by calculating the compensation factor ($C_l$) for a range of wavelengths, we determine $F_l$, the ratio of the resultant topography to the initial load topography. Here $l$ is the spherical harmonic degree, related to the wavenumber ($k$) by $l \approx kR_0 - \frac{1}{2}$, where $R_0$ is the radius of the body. $C_l$ is calculated using equation (27) from Turcotte et al. (1981) and determines the degree to which the topography is compensated by elastic and membrane support. As $C_l$ approaches 0, the resultant topography is equivalent to the initial load topography. However, as $C_l$ approaches 1, the resultant topography depends on the density difference between the two rheologically distinct sections of the ice shell. With the values from Table 1 for $\rho_c$, the density of the elastic section of the crust (assumed to be pure-water ice), and $\rho_m$, the density of the ductile ice
immediately beneath the elastic layer, \( F_l \) approaches 1/47. We can use \( C_l \) to determine \( F_l \) as follows:

\[
F_l = \frac{1}{1 + \left( \frac{\rho_e - \rho_c}{\phi m - \rho_c} \right) C_l}
\]

For our calculations we consider two approaches to calculating \( C_l \). The first assumes a Cartesian geometry with no effects due to the sphericity of the world and the second includes membrane support from a spherical body. Once we determine \( F_l \), we take the square of the value \((F_l^2)\) and multiply it with an initial topographic variance spectrum that conforms to a single power law slope equal to the short-wavelength portion of Pluto or Charon’s measured topographic variance spectrum. We use \( F_l^2 \) as the variance is calculated from the summed squares of the spherical harmonic coefficients. The results for both Pluto and Charon, with a variety of different possible elastic layer thickness, are presented in Figure 7. For both bodies with either models an increase of ~50 km in the elastic layer translates to about an order of magnitude increase in the topographic variance at the longest wavelengths.

**Table 1.** Parameters used in this study.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value (P), Charon (C)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g )</td>
<td>Surface Acceleration due to Gravity</td>
<td>P: 0.62 m s(^{-2}) C: 0.288 m s(^{-2})</td>
<td>Stern et al., 2015</td>
</tr>
<tr>
<td>( R_\theta )</td>
<td>Body Radius</td>
<td>P: 1188.3 km C: 606 km</td>
<td>Nimmo et al., 2017</td>
</tr>
<tr>
<td>( M_p )</td>
<td>Mass of Pluto</td>
<td>1.3 x 10(^{22}) kg</td>
<td>Stern et al., 2015</td>
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<tr>
<td>( \rho_c )</td>
<td>Crustal density</td>
<td>920 kg m(^{-3})</td>
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<tr>
<td>( \rho_m )</td>
<td>Density of the ductile crust</td>
<td>940 kg m(^{-3})</td>
<td></td>
</tr>
<tr>
<td>( E )</td>
<td>Young’s Modulus</td>
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</tr>
<tr>
<td>( \nu )</td>
<td>Poisson’s Ratio</td>
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<td>Gammon et al., 1983</td>
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<td>( Q )</td>
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<td>Goldsby and Kohlstedt, 2001</td>
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<td>Mancktelow, 1999</td>
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<tr>
<td>( \mu )</td>
<td>Rigidity modulus</td>
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<td>( \mu = E/(2(1+\nu)) )</td>
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<td>( d )</td>
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<td>( T_s )</td>
<td>Surface temperature</td>
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<td>Stern et al., 2015</td>
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<td>( \kappa )</td>
<td>Thermal</td>
<td>567/T W m(^{-1})</td>
<td>Klinger, 1980</td>
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conductivity of pure H₂O ice

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<tr>
<th><em>a</em></th>
<th>Charon-Pluto Initial Semi-Major Axis</th>
<th>$\sim 1.5 \times 10^4$ km</th>
<th>About 75% of modern; Stern et al., 2015</th>
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<th><em>k</em>/Q</th>
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<th>$\sim 0.2$</th>
<th>Upper limit; Chen and Nimmo, 2008</th>
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<th><em>e</em></th>
<th>Initial orbital eccentricity of Charon</th>
<th>$10^{-1}$ to $10^{-2}$</th>
<th>Canup, 2011</th>
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</table>

Table 1 notes:

- a - Basal slip-accommodated grain boundary sliding (GBS) regime
- b - GBS-accommodated basal slip regime
- c - Dislocation creep regime

**Figure 7.** Modeled variance spectra compared with our limb profile spectra. 

**a.** Pluto’s topographic variance spectrum with compensation model results overlain. The solid lines are from the cartesian model, and dashed lines are the spherical with membrane support. Lines shift in hue from red to blue as the thickness of the elastic layer increases. The primary observation of the results for Pluto are that a thicker elastic layer improves the fit of both models, but the lack of a break in slope only allows for a minimum thickness to be determined.

**b.** Charon’s topographic variance spectrum with compensation model results overlain. The solid lines are from the cartesian model, and dashed lines are the spherical with membrane support. Lines shift in hue from red to blue as the thickness of the elastic layer increases. Due to the break in slope a range of elastic thicknesses can be determined instead of a minimum as with Pluto.
Because Pluto’s variance spectrum lacks a break in slope, our flexural models only place a lower bound on the elastic thickness. For either model, we would expect to see a statistically significant break (Figure 6) if the elastic thickness was less than ~60 km during and after the period of topography formation. The exact timing of this is relevant, as the elastic thickness could have been lower at times prior to the formation of the topography captured in limb profiles.

With Charon, however, the compensation model results roughly agree with the results of the straightforward assumption that the break in slope wavelength represents the flexural parameter value. The cartesian case gives a slightly higher elastic layer thickness (compared to the flexural parameter assumption) of ~20±10 km, while the spherical case with membrane support implies much lower values for possible elastic thicknesses (<5 km). As we discuss below, the latter value would imply a much higher heat flux than reasonably possible (McKinnon and Nimmo, 2020), so we conclude that membrane support is not operating on Charon. The most reasonable explanation for this is that, as on the Earth, Charon’s lithosphere is sufficiently fractured that long-distance transmission of membrane stresses is not possible. Since there is extensive evidence for large-scale faulting on Charon (Beyer et al. 2017) this explanation seems plausible.

3.4 Heat flux

With estimates for the elastic thickness – a lower bound for Pluto and a likely range for Charon – we can further estimate the thermal structure of either body’s icy crust at the time of load emplacement. Although there are various methods to solve for the temperature at the base of the elastic layer ($T_b$), we will use the method outlined in Conrad et al. (2019). We assume that any of the three most important ice deformation regimes can be dominant and as such use the cumulative strain relationship (Goldsby and Kohlstedt, 2001).

$$\dot{\varepsilon}_{\text{comp}} = \left( \frac{1}{\dot{\varepsilon}_{\text{gbs}}} + \frac{1}{\dot{\varepsilon}_{\text{basal}}} \right)^{-1} + \dot{\varepsilon}_{\text{dis}} \tag{4}$$

Here $\dot{\varepsilon}$ is the strain rate (s$^{-1}$) and gbs, basal, dis, and comp correspond to basal slip-accommodated grain boundary sliding (GBS), GBS accommodated basal slip, dislocation creep, and composite (i.e. cumulative) respectively. The equation and respective parameters for the strain rate in each regime can be found in Goldsby and Kohlstedt (2001), but the important values we consider are $T_b$ and $\sigma_{\text{crit}}$, the critical stress at $T_b$ that can be determined with:

$$\sigma_{\text{crit}} = De \ast \mu \tag{5}$$

Here $\mu$ is the shear modulus of water ice and $De$ is the Deborah number (Mancktelow, 1999), a dimensionless number that gives the strain rate where the transition from the elastic layer to the viscous layer based on the crust’s Maxwell time. We use a different range of $De$ ($10^{-3}$ to $10^{-4}$) as compared with the previous study of Pluto’s heat flux (Conrad et al., 2019; $10^{-2}$ to $10^{-3}$). For the upper value of $De = 10^{-3}$, we chose that value as it is consistent with the thermal state and measured elastic thicknesses of the terrestrial oceanic lithosphere (Watts, 2001). However, for
the lower value of $De = 10^{-4}$, we base this on our estimation of faulting-induced stresses (section 4.3). If we apply the maximum stress of a few hundred kPa to equation 5, we get the $De$ of $\sim 10^{-4}$.

We can now calculate $\dot{\varepsilon}$ given a set of $T_b$, $De$, and other important parameters (most notably grain size). The range of reasonable grain sizes (1 mm to 10 cm) is set by the results of Barr and McKinnon (2007) and the expectation that the material properties of Pluto and Charon’s icy crusts will not differ much from large icy satellites. Our results for the relationship between $\dot{\varepsilon}$ and $T_b$ are presented in Figure 8a and show that higher strain rates imply higher temperatures at the base of the elastic layer.

Figure 8a shows that as $\dot{\varepsilon}$ varies over the range of plotted values ($10^{-20} \text{ s}^{-1}$ to $10^{-14} \text{ s}^{-1}$), $T_b$ can vary over 30 K. While narrowing down $\dot{\varepsilon}$ would allow for $T_b$ to be better determined, at present, we can only define a range of reasonable values for $\dot{\varepsilon}$. Our two endmembers for the value of $\dot{\varepsilon}$ are based on likely aspects of Pluto and Charon’s geophysical history. For the lowest values of $\dot{\varepsilon}$ we look at the results of thermal evolution models (e.g. Hammond et al., 2016; Bierson et al., 2018), where the strain rate is driven by the rate of freezing of the subsurface ocean. For Pluto and Charon, the amount of strain calculated by these models is $\sim 1\%$. If we assume that this strain is continuously generated over the extensional history of both bodies, then the strain rate is $\sim 10^{-19} \text{ s}^{-1}$. Additionally, given Charon’s greater amount of strain (about twice the amount) and likely faster freezing rate the strain rate in that estimate could be higher for the moon. The high value endmember assumes that the entirety of Pluto and Charon’s topography is generated by the stresses from a true polar wander event (TPW; Keane et al., 2016; Nimmo et al., 2018). If we take the timing estimate from Keane et al. (2016) of $\sim 5$ million years, the strain rate should be $\sim 10^{-16} \text{ s}^{-1}$. From the two endmembers, our reasonable strain rates are between $10^{-19}$ and $10^{-16} \text{ s}^{-1}$.

To find the surface heat flux from the elastic layer base temperature values, we additionally need the thickness of the elastic layer (determined from the compensation analysis) and the thermal conductivity of ice ($\kappa$). We use the temperature dependent form of $\kappa$, which varies as $567/T$ (Klinger, 1980). Because the dual-synchronous orbit should be reached rapidly in the dynamical evolution of both bodies, we neglect any source of tidal heating in the ice shell. We do not consider effects due to porosity, although including porosity would result in a lower estimated heat flux. The heat flux $F$, with surface and basal temperatures $T_s$ and $T_b$, respectively, is given by:

$$ F = \frac{567 \ln(T_b/T_s)}{t_e} \quad (6) $$

Figure 8b shows how the surface heat flux depends on both the basal temperature and the elastic thickness. Contours of constant heat flux are plotted with regions that fit with our elastic thickness results highlighted in boxes. We also note the expected surface heat flux if radiogenic heat sources are the sole heating factor ($\sim 3-6 \text{ mWm}^{-2}$; Nimmo and McKinnon, 2020).
Figure 8. Rheologic and heat flux model results for Pluto and Charon. A. Temperature at the base of the elastic layer over a range of strain rates for a variety of rheologic parameters. The results for $De = 10^{-3}$ start to show the trade-off between the dislocation creep and grain-boundary dependent regimes. At the lower $De$ of $10^{-4}$, the transition between the same regimes and how they depend more on the grain size as grain-boundary dependence regimes starts to dominate. B. “Heat” map of surface heat flux as a function of the elastic layer thickness and basal temperature. Contours for 10, 20, 30, 50, 75 and 100 mWm$^{-2}$ are plotted in white. Dashed boxes define our estimates for the possible range of heat fluxes for Pluto and Charon.

For Pluto, our minimum elastic thickness of 60 km gives a maximum surface heat flux since topography formation of $\sim$13 mWm$^{-2}$, if we assume that all topography was generated due to TPW stresses (i.e. $\dot{\varepsilon} = 10^{-16}$ s$^{-1}$) and the higher temperature rheology is the active case (i.e. $De = 0.001$). In our more conservative case where the topography forms over the entire lifetime of Pluto (i.e. $\dot{\varepsilon} = 10^{-19}$ s$^{-1}$) with the lower temperature rheology, the maximum heat flux is reduced to $\sim$10 mWm$^{-2}$. This maximum constraint is consistent with radiogenic heating estimates, and smaller compared to the previous upper bound of 66-85 mWm$^{-2}$ from a lack of flexural signals at Pluto’s faults (Conrad et al., 2019). Although there are still individual features on the surface of Pluto, notably Edgeworth crater that may imply a higher heat flux (McKinnon et al., 2017), these are now harder to reconcile with our new, lower heat flux constraints. Conversely, these heat flux bounds are not in contradiction to the “hot start” model of Pluto (Bierson et al. 2020), as long as the topography was created at least a few tens of Myr after Pluto formed.

Since Charon has a range of possible elastic thicknesses rather than a lower bound, we can use this to determine a range of possible surface heat fluxes. For our estimate of $\sim$20±10 km with the range of rheological parameters, we get a heat flux range of 35$^{+44}_{-15}$ mWm$^{-2}$. With a thinner elastic layer (10 km), TPW stresses (i.e. $\dot{\varepsilon} = 10^{-16}$ s$^{-1}$) and the higher temperature resultant rheology (i.e. $De = 10^{-4}$), we get the high end of our surface heat flux range: 79 mWm$^{-2}$. This value is
approximately in the same range as average surface heat fluxes for tidally heated icy satellites (e.g. Giese et al., 2007; 2008) and would require a larger heat source than can be provided by radiogenic heat production, either today or in the past. On the low end of our estimate \(\sim 20\text{ mWm}^{-2}\), which is achieved by the more conservative ice shell freezing strain rate (i.e. \(\varepsilon = 10^{-19}\text{ s}^{-1}\)), a higher \(D_e\) of \(10^{-3}\), and a thicker elastic layer during topography formation (i.e. 30 km), we still have a value that is higher than radiogenic. These results suggest the existence of a heat source for Charon in addition to radiogenic heat; we will review various hypotheses for this unknown heat source in the following discussion.

4 Discussion

4.1 Early heat sources for Charon

The elastic thickness derived for Charon provides an estimate of the surface heat flux during the period of topography formation that is difficult to reconcile with results that model a purely radiogenic heat source (Bierson et al., 2018). There are a few, shorter lived, heat sources that could have increased the available heat during topography formation. The two that we will elaborate on are heat from accretion, especially if Charon was formed in a giant impact (Canup, 2011), and tidal deformation while Charon’s orbit circularizes (Barr & Collins, 2015; Rhoden et al., 2020).

4.1.1 Heat from a Charon forming giant impact

One of the more popular hypotheses for the formation of Charon involves a giant impact into a proto-Pluto (Canup, 2011). A newly formed Charon would either coalesce out of orbiting debris or directly form from the largest intact fragments (Arakawa et al., 2019). In either case, depending on the parameters of the impact, Charon could form partially melted. Smooth particle hydrodynamics impact simulations from Canup (2011) and Arakawa et al. (2019) record the state and temperature of particles through the simulations. Canup (2011) found that the temperature increase in the impact is concentrated towards the outer layers. This temperature increase is enough to melt around 10% of the bulk volume if the increase is focused in water ice. Melting introduces heat into the body that needs to radiate away before it can refreeze. If 10% of Charon (~1.6 x 10^{20} \text{ kg}) melts, the energy released upon refreezing is \(\sim 5 \times 10^{25}\text{ J}\). On a per area basis, this would mean that \(\sim 10^{13}\text{ Jm}^{-2}\) needs to radiate. If we consider our moderate surface heat flux result (~35 mWm^{-2}), Charon’s initial heat budget would be largely exhausted after \(~15\text{ Myr}\). An interval of \(~15\text{ Myr}\) to generate the bulk of Charon’s topography (as recorded by limb profiles) is quite short, but perhaps not completely unreasonable.

4.1.2 Charon tidal heating

Presently, Pluto and Charon are caught in a double tidally locked state, where they constantly face each other in their circular orbits. This orbital configuration does not cause a temporally variable tidal deformation and as a result cannot generate heat, but Charon’s orbit was probably initially more inclined and/or eccentric. Either of those orbital states can generate heat if the body can be tidally deformed. However, since we do not know the initial state of the orbit, we need to assume an initial state based on formation models (Canup, 2011; Arakawa et al., 2019).
Unlike the distribution of increased temperature, the range of possible eccentricities is wide. Below we neglect any obliquity tidal heating due to an initial inclination, and only look at the effect due to eccentricity tides.

Possible eccentricities for a newly formed Charon can reach values near 1.0 (Arakawa et al., 2019). Eccentricities that high would reduce rapidly, especially if Charon were molten, and the heating during these periods would be brief. Modelling the tidal evolution during this period is especially complicated given the change in the deformability and rigidity (i.e. the $Q$ and $k_2$ values). To estimate the heat flux during periods of different eccentricities we use a simplified version of the equation which calculates the surface heat flux due to synchronous tidal deformation (Murray and Dermott, 1999; equation 4.197):

$$\text{Heat Flux} = \left( 15320 \text{ mW m}^{-2} \right) \left( \frac{13,720 \text{ km}}{a} \right)^{15/2} \left( \frac{k_2/Q}{0.2} \right) \left( \frac{e}{0.1} \right)^2$$  \hspace{1cm} (7)

Here the poorly constrained parameters are $a$, the semimajor axis of Charon’s orbit around Pluto, $k_2$ is the Love number, $Q$ is the dissipation factor, and $e$ is the eccentricity of the orbit. Estimated values for these variables are presented in Table 1. For $a$ we assume a nominal initial semimajor axis about 70% of Charon’s current orbit ($a_{\text{modern}} \sim 2 \times 10^4 \text{ km}$). The importance of this term is clear from the high exponent (15/2) that governs it, although we do not expect it to start much lower than our estimate. $k_2/Q$ is the term that describes the internal structure and rigidity of the body. A lower $k_2/Q$ signals a more rigid body that cannot deform as easily and create heat. We assume, based on the results of Arakawa et al. (2019), that Charon was initially partially molten (i.e. fluid). Following those results we look to other bodies in the solar system and base our upper limit $k_2/Q$ for Charon on Tethys results (Chen and Nimmo, 2008), since Tethys has a similar radius to Charon. This effect of this parameter is linear when applied to equation 7, although the parameter itself is highly unconstrained. A common initial eccentricity used in tidal stress studies of Charon (e.g. Rhoden et al., 2020) is 0.01. This eccentricity with a lower $k_2/Q$ of 0.01 would yield a surface heat flux of $\sim 8 \text{ mW m}^{-2}$, at least a factor of two smaller than the smallest value we estimate from our derived elastic thickness values. However, an eccentricity of 0.1, which is on the lower end of those predicted from giant impact simulations (Canup, 2011), with a $k_2/Q$ of 0.2 would yield $\sim 15 \text{ W m}^{-2}$, a value an order of magnitude higher than present-day Io. Thus, either (or more likely both) the $k_2/Q$ or the eccentricity must have been lower during the tidal heating period. While our derived heat fluxes during topography formation are certainly consistent with possible tidal heat production on Charon, the uncertainties in the latter are very large.

One issue with the high eccentricity estimate is that, if topographic loads were emplaced during this period, we would also expect to see the faulting of Charon fit the stress pattern caused by eccentricity tides (Rhoden et al., 2020). Rhoden et al., however, did not find a fit between their modelled stress patterns and the observed tectonics. The timing of topography formation is thus crucial: if the topography formed after Charon’s orbit circularized, as Rhoden et al. (2020) postulate, then there needs to be a way for the ice shell to have remained thin once the orbit became circular. One possible solution to this problem is latent heat: tidal heating may have been stored as ice (or silicate) melts, which would provide a reservoir of heat released slowly after
circularization was complete. Further investigation of Charon’s early thermal evolution including tidal heat production is clearly warranted.

4.2 Comparisons with previous Pluto/Charon topographic variance results

The variance spectra presented in this work are the first for Pluto and Charon based on limb profile topography. However, variance spectra of Pluto and Charon have also been presented in Ermakov et al. (2018). They used the published DEMs (Schenk et al., 2018a & 2018b) to calculate estimates for spherical harmonic coefficients. Since the DEMs only cover 30-40% of the surface area of Pluto and Charon they created their data using spectral-spatial localization techniques (Wieczorek & Simons, 2005; Simons & Dahlen, 2006). With those spherical harmonic coefficients, they were able to calculate the variance spectra in a similar manner as we did with Fourier series coefficients. The major difference is that spherical harmonics are two dimensional and Fourier series have just a single dimension.

Ermakov et al. (2018)’s data is available as root mean squared (RMS) values, which are normalized by the radius. These values are different from what we present in Figure 5, which are the (non-normalized variances) for the two worlds. Our values are useful for understanding the observed variations in the topography in kilometers, and theirs are more useful for the comparison of multiple different bodies. We convert our variance spectra to RMS spectra following equations (4), (6), and (8) from Ermakov et al. (2018). The spectral comparison is shown in Figure 9.
Figure 9. RMS spectra comparison of Ermakov et al. (2018) and this study. The data from Ermakov et al. (2018) is presented as solid lines, and the data from this study as the binned average with shaded regions of the standard deviation within the bin. Color matches those used in Figure 6 and 8b. Shorter wavelengths for Charon match well, and longer wavelengths are within the standard deviation. However, there is an observable mismatch of the values for Pluto.

Our results for Charon show that Ermakov et al. (2018) could not have observed the break in slope given their limited wavelength range. At short wavelengths the RMS values and slopes are almost identical between the two approaches, but these diverge somewhat at long wavelengths, perhaps because of the difference between 1D and 2D analyses. However, when Pluto is compared, although the slope differences are similar to those of Charon (both limb profile spectra are steeper by ~0.5 compared to DEM-derived spectra slopes), we see a large discrepancy in the RMS values. The most likely explanation for this large difference is that the geographical coverage of the two data sets is very different. In particular, the most obvious
4.3 Stresses induced by faulting

Once the elastic thickness of a layer has been determined, we can estimate the maximum stress \( \sigma_{\text{max}} \) a fault is required to support to maintain the observed topography. Such maximum stresses have previously been determined for Pluto (Conrad et al., 2019) and Charon (Beyer et al., 2017); the difference in this study is that the elastic thickness derived is different. We use the set of equations from Jackson and White (1989) to calculate \( \sigma_{\text{max}} \):

\[
\sigma_{\text{max}} = \frac{\rho g \lambda}{2e} \quad \text{if } \frac{\lambda}{t_e} < \frac{\pi}{2} \quad \text{(8)}
\]

\[
\sigma_{\text{max}} = \frac{3 \rho g h \lambda}{8 \pi^2 t_e^2} \quad \text{if } \frac{\pi}{2} < \frac{\lambda}{t_e} < \frac{\pi}{2} \quad \text{(9)}
\]

\[
\sigma_{\text{max}} = \frac{3 \rho g h \lambda^2}{8 \pi^2 t_e^2} \quad \text{if } \frac{\lambda}{t_e} > \frac{\pi}{2} \quad \text{(10)}
\]

Here \( 2h \) is the vertical displacement of the fault, \( e \) is the base of natural logarithms (not the orbital eccentricity), and \( \lambda \) is the wavelength of the faulting width (twice the trough width in most cases). All other variables are the same as described in previous equations. Stresses must support the gravitational load of the faults to maintain topography; otherwise the faults would move in such a way as to reduce the topography (Jackson and White, 1989).

For Pluto, the major faulting in Viking and Cthulhu regions have widths (i.e. \( \lambda/2 \)) on the order of 20km and throws (i.e. \( 2h \)) around 2km. Thus, given our minimum elastic thickness of \( \sim 60 \) km, the largest observable faults on Pluto fall within \( \frac{\lambda}{t_e} < \frac{\pi}{2} \) as \( \lambda/t_{e, \text{min}} \) is near unity. Equation (8) is thus relevant to all faults on Pluto and implies that the value of \( \sigma_{\text{max}} \sim 100 \) kPa. This matches previous results (Conrad et al., 2019) and does not imply any significant changes to how we view those faults.

However, on Charon, our new estimate of \( t_e \) (20 ± 10 km) is nearly an order of magnitude higher compared to previous results (2.5 km; Beyer et al., 2017). We can take the range of observed tectonics on Charon and apply values from Table 1 to equations 8 through 10. For \( h \) we assume a value of 2 km from the throw of Serenity Chasma (~ 4 km; Beyer et al., 2017) and for \( \lambda \) we use the geometry of Serenity Chasma as well (~50 km). We find that \( \sigma_{\text{max}} \sim 105 \) to 500 kPa, which is equal to or higher than what we infer for Pluto but at the high end is the same order of magnitude as a previous estimate for faults on Europa (Nimmo and Schenk, 2006). Since the depth at which a frictional stress of 500 kPa would be reached is about 3 km on Charon, it is evident that faults on Charon need not be abnormally strong to withstand the imposed topographic stresses. This evidence for a higher value of \( t_e \) resolves the paradox noted in Beyer et al. (2017).

5 Conclusions

In this study we have carried out a spectral analysis of limb profile data for Pluto and Charon. These data complement previously derived DEM topography (Schenk et al., 2018a and 2018b) and provide longer baselines to analyze. The topographic variance spectra of these two bodies
reveal stark differences between them in how topography is distributed over the range of observed wavelengths. While Pluto exhibits a topographic variance spectrum that can be characterized by a single slope power law, which is common for other worlds (Ermakov et al., 2018), Charon’s topographic variance spectrum has a break in slope. This might imply relaxation or lack of topography with wavelengths greater than that of the break in slope. Making a flexural interpretation, we determine that Charon had a thin elastic ice shell ($t_e = 20 \pm 10$ km) during the period of topography formation, which had to be driven by a high surface heat flux ($35^{+14}_{-15}$ mWm$^{-2}$). This high surface heat flux requires heat sources beyond radiogenic, either from a giant impact formation for Charon or (more likely) tidal heating from the circularization of Charon’s orbit. These constraints may be used in future work to probe the early evolution of both Pluto and Charon.

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Data Availability Statement

The limb profile topography, processed limb profile, and topographic variance spectra for Pluto and Charon can be found via Dryad at https://datadryad.org/stash/dataset/doi:10.7291/D16H3S (Conrad, 2020). The base images used to derive limb profile topography can be found at OPUS, the Outer Planetary NASA mission data website in the Planetary Data System (https://opus.pds-rings.seti.org/opus/).

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