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**Introduction:** In 2015, the *New Horizons* spacecraft flew past Pluto and its moon Charon, providing the first glimpse of their surfaces. Among other things, *New Horizons* images of Charon revealed an ancient surface, a hemisphere-scale canyon system, and numerous fractures [1]. Here, we assess whether tidal stresses led to the formation of Charon’s fractures. Although presently in a circular orbit, most scenarios for Charon’s orbital evolution include an eccentric orbit for some period of time [e.g. 2] and possibly an internal ocean [3,4]. Past work [5] has shown that these conditions could have generated stresses comparable in magnitude to other tidally-fractured moons, such as Europa and Enceladus. Here, we compare the orientations of Charon’s observed tectonic features, mapped and classified as tensile in origin by [1], and compare them with the orientations of fractures that would form due to eccentricity-driven tidal stress.

**Methods:** We computed tidal stresses using our code, SIMON, which is built upon the viscoelastic formulation of [6]. We have previously used this code to assess stresses on Europa [7], Mimas [8], Enceladus [9], and pre-encounter Charon [5]. To compute stresses, we specify the thickness and material properties of five internal layers, as well as orbital parameters such as eccentricity. We ensure that our selections of layer thickness and density combine to match Charon’s observed radius and density, as determined from *New Horizons* data [10]. All of our interior structures include a hydrosphere that is 230 km thick; it is comprised of a liquid water ocean overlain by an ice shell that has a brittle upper layer and ductile lower layer. Given the large uncertainties in Charon’s structure and material properties, we varied only a few parameters, which our past work has shown to have the largest impact on tidal stresses. Specifically, we varied the thickness of the ice shell (versus ocean) and the viscosity of the ductile ice layer.

We compute stresses on a latitude-longitude grid; at each location, we calculate stress at 360 steps through Charon’s orbit. We then determine the orientation of the largest stress at each time step. At times when the stress is both tensile and increasing, we assume a fracture can form at an orientation perpendicular to the stress direction, as is typical for mode 1 cracks. We set no requirement on the magnitude of the stress required for fracture formation, because 1) the failure strength of Charon’s ice shell is unknown and 2) changing the eccentricity would change the stress magnitude, so any failure threshold we select could yield many possible fractures or none at all. We expect that orientations associated with higher stresses are more likely to form, but we include all possible orientations in our results. Because the eccentricity only changes the magnitude of stress, not its orientation, we select an arbitrary value of $e=0.1$ and hold it constant. We also use Charon’s current semimajor axis, although Charon almost certainly formed closer to Pluto and tidally-evolved outward.

**Results:** We find that all interior structure models produce a similar pattern of tidally-driven fractures. An example is shown in Figure 1. Observed fractures, represented by green lines at their measured orientations, have been binned into the same latitude-longitude grid as our predictions, which are shown in grey. The pattern is mirrored across the equator due to symmetries in the stress field. Eccentricity stresses would generate mainly northwest-southeast trending fractures north of the equator and northeast-southwest trending fractures south of the equator. Poleward of about 60° latitude, the predicted orientations are longitude dependent and cycle through all possible orientations.

Due to potential differences in age and geologic activity, we also divide our comparisons into two regions: one within Oz Terra to the south (Region A) and one that covers most of Vulcan Planum in the north (Region B). The orientation histograms in Fig. 1 show the results for each region; green represents observed fractures while grey represents the predictions.

**Discussion:** Tidal stress magnitudes: Across all interiors we tested, tidal stresses are comparable to (although slightly lower than) those inferred for Europa and Enceladus (3 – 49 kPa) and an order of magnitude lower than the failure strength of pure water ice in laboratory tests. Although the distance between Pluto and Charon is much smaller than the distance to the primary bodies of those icy satellites, Pluto’s mass (and thus tide-raising potential) is much lower, so it is reasonable that the magnitudes are comparable. Also, the tidal stress magnitudes would increase with a higher past eccentricity and/or a smaller semi-major axis. If Charon had an internal ocean during its orbital migration, and particularly if it were inducing stresses by freezing [11], it is possible that tidally-driven fractures formed on the surface. However, within Charon’s geologic record, we see no evidence of fractures associated with eccentricity tidal stress.
Tidal stress orientations: Looking globally, the majority of Charon’s observed fractures trend northeast-southwest with a broader range of orientations than the tidal predictions. While the observations align somewhat within Oz Terra (south of the equator; Region A), the observed fractures lack the mirroring expected of tidal fractures, so the two are not well correlated through much of Vulcan Planum (north of the equator; Region B). One might suppose that the fractures that fit the predictions are the remaining population from a time of tidally-driven activity. However, cratering ages suggest that Oz Terra is slightly younger than Vulcan Planum [12], casting doubt on that hypothesis. It is also important to note that shifting features in longitude would not improve the match between the predictions and observations, so non-synchronous rotation cannot explain the mismatch.

The lack of a tidal signal within Charon’s fracture patterns leaves us with two questions: 1) what created the observed fractures and 2) why don’t we observe fractures associated with eccentricity? It has been suggested that fractures in Oz Terra are related to the cooling of a cryomagmatic flow [1]. In Vulcan Planum, a large canyon system dominates the tectonic record. It’s formation has been attributed to freezing of an early ocean [1,3,4], which would cause a volume increase and tension in the overlying ice shell. To test these hypotheses, it may be possible to create predictions of the fractures patterns associated with each geophysical process that could be tested against the observations.

The lack of eccentricity-driven fractures implies that either these stresses were never large enough to cause failure on Charon or that the epoch of fracture formation occurred early enough in Charon’s history that the fractures could be obscured by the formation of the chasmas in Vulcan Planum, the flows in Oz Terra, and subsequent cratering. To avoid fracturing altogether, Charon’s orbit must have circularized before its ocean froze. Otherwise, the large stresses caused by ocean freezing should have enhanced the eccentricity stress pattern [11]. This sequence of events makes sense because circularization would have reduced tidal heating, encouraging freezing of the ocean, allowing a timescale constraint on circularization to be set.

Acknowledgments: This work was supported by the New Horizons mission. The abstract was written by AR while caring for two small children with week-long fevers of 103°. AR wishes to thank her colleagues and friends for their support and patience, which greatly aided in the completion of this abstract.

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Figure 1: The predicted orientations of fractures caused by eccentricity-driven tidal stress (grey) are a poor match to the observed fracture orientations (green). Globally, the observed fractures lack the equatorial symmetry present in tidal stress patterns. In Oz Terra (Region A), the observed orientations overlap the predicted ones, but the range is much broader. In Vulcan Planum, the observed fractures are slightly more concentrated between 75 and 90° (with 90° being E-W). However, the predictions are for fractures with orientations ≥ 75°, and the distributions are quite dissimilar, as shown in the Region B histogram in Figure 1. All interior structures we tested result in essentially the same pattern of predicted orientations. Hence, it seems highly unlikely that the observed fracture population on Charon formed in response to eccentricity-driven tidal stress. Non-synchronous rotation is also not supported as there is no longitude at which the predicted fracture pattern is observed.