RECONSTRUCTING RIVER FLOWS ON EARTH, MARS, AND TITAN. S.P.D. Birch[1], G. Parker[2], P. Corlies[1], J.W. Miller[3], J.M. Soderblom[1], R. Palermo[1,4], J.M. Lora[5], A.D. Ashton[4], A.G. Hayes[6], and J.T. Perron[1], [1]MIT (sbirch@mit.edu), [2]University of Illinois, [3]UCLA, [4]WHOI, [5]Yale, [6]Cornell.

Introduction: Rivers are among the clearest manifestations of the hydrologic systems of Saturn's moon Titan and ancient Mars. Titan has an active hydrologic cycle currently shaping the landscape[1], with river networks (Figure 1f/g), possible river deltas, and vast seas of liquid methane and ethane that may be experiencing sea level change[2]. However, much remains unknown about Titan's hydrologic cycle and climate, including the rates of precipitation and runoff, the resulting rates of erosion and sediment deposition, and spatial and temporal climate variations. On Mars, ancient river channels crossing many of its landscapes and depositional fans and deltas in some impact craters (Figure 1d/e) imply past runoff. Yet the intensity and duration of the runoff lack definitive constraints, and the nature of the ancient climate that produced it remains an intensely studied problem[3].

River channels offer clues about the environments in which they form, and may therefore hold the keys to unlocking some of these mysteries about Titan and Mars. In particular, alluvial rivers, which construct their own channels with the sediment they carry (Figure 1a), adjust their width, depth, and slope in response to the fluxes of fluid and sediment they convey[4-6]. Fluid and sediment fluxes in turn reflect various aspects of a planet's surface environment, from the rates of precipitation and runoff that produced the flow to the upstream erosion that generated the sediment.

Previous estimates of fluid and sediment discharge in rivers on Titan[7] and Mars[8] have typically relied on estimates of flow depth, bed sediment grain size, or sediment concentration, each of which is difficult or impossible to measure without direct surface observations or active flow. Titan's active river flows are not well resolved by current spacecraft data, and Mars' rivers no longer flow. Although granular sediment exists on both Mars and Titan (Figure 1b/c), such surface observations are rare. It would be preferable to reconstruct planetary rivers using quantities that can be measured from orbit even in the absence of active flow.

On Earth, empirical equations calibrated from field measurements are commonly used to relate a river channel's width, depth, and slope – its hydraulic geometry – to flow discharge, sediment flux, and other properties[4-6]. This approach has the advantage of using characteristics that can be measured remotely, such as width and slope, but it has not been widely applied to planetary rivers. This is because the empirical constants in conventional hydraulic geometry equations do not account for conditions that differ between planets, such as gravity (which differs on Titan and Mars) fluid and sediment density, and because it is currently impossible to calibrate hydraulic geometry equations for Titan and Mars with field measurements.

Therefore, we adapt recently proposed dimensionless hydraulic geometry equations[4-6] to reconstruct characteristics of planetary rivers using only channel width and slope, both of which can be measured from orbit. We calibrate these equations, which explicitly account for gravity and fluid/sediment density, with a compilation of alluvial river characteristics on Earth. Applying this theory to rivers on Titan and Mars, we estimate rates of flow and sediment discharge that offer insights into Titan's active hydrologic cycle and Mars' ancient climate as well as highlighting observational targets for landed and orbiting spacecraft.

Dimensionless Hydraulic Geometry: Parker et al.[4,5] and Wilkerson and Parker[6] proposed universal

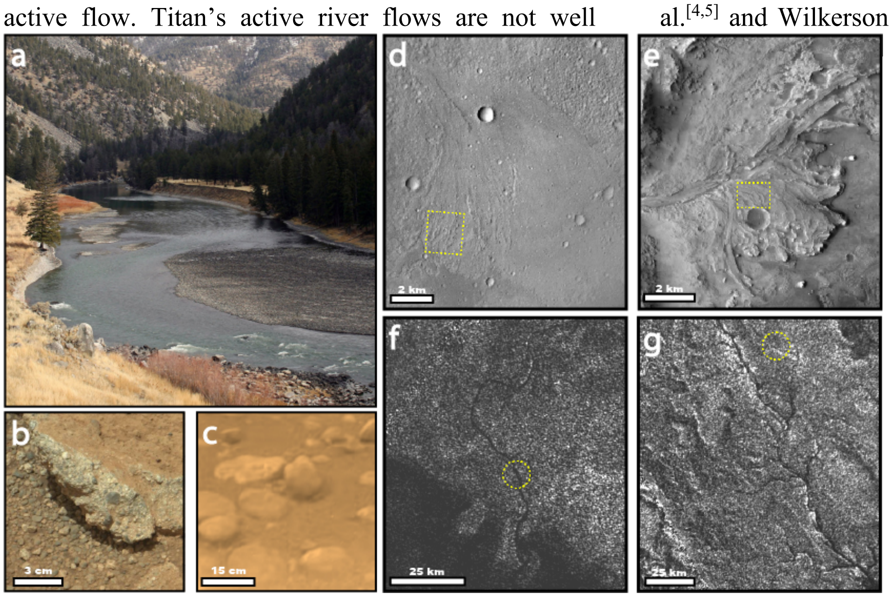

Figure 1: (a) The Yellowstone River, with gravel-bed and banks; In situ images of gravel on both Mars (b) and Titan (c) from the *Curiosity* rover and *Huygens* lander respectively; (d) Peace Vallis fan, an alluvial fan within Gale Crater on Mars; (e) The western delta within Jezero Crater on Mars, the target of exploration for the *Perseverance* Rover; (f) Saraswati Flumen on Titan, terminating in two delta-like lobes along the western shoreline of Ontario Lacus; (g) Vid Flumina on Titan, a large tributary network that terminates at Ligeia Mare.

hydraulic geometry relationships for gravel-bed and sand-bed rivers; dimensionless bankfull channel width ($\tilde{B} = \frac{g^{0.2}B}{Q^{0.4}}$), slope ($S$), depth ($\tilde{H} = \frac{g^{0.2}H}{Q^{0.4}}$), and bedload (gravel) or total load (sand) sediment flux ($\hat{Q}_s = \frac{Q_s}{g^{0.5}D_{50}^{2.5}}$) are power-law functions of the dimensionless discharge ($\hat{Q} = \frac{Q}{g^{0.5}D_{50}^{2.5}}$). B, H, Q, and Q_s are the dimensional quantities, and D_{50} is the median bed grain size. The dimensionless quantities account for gravity (g), with power-law coefficients being functions of the sediment (ρ_s) and fluid densities (ρ). obtained by combining equations for flow resistance and sediment transport with a channel width theory that relates the bed shear stress to the critical shear stress for grain entrainment[5].

Unlike on Earth, where river channel width and slope, bed grain size, flow depth and discharge, and sediment flux can be measured in the field, river characteristics on Titan and Mars must be measured from remote sensing data. On Titan, the Cassini spacecraft's images of the surface (~1 km resolution) make it possible to place bounds on channel width, and Cassini RADAR altimetry data permit measurements of channel slope in a two locations. On Mars, remote sensing images and topographic data provide meter-scale views of the surface in many locations. However, most features of interest have been degraded by billions of years of aeolian erosion, such that the river characteristics that can be estimated most reliably are the present-day width and slope of inverted channel beds[9,10].

Due to these limitations, we rearrange the original dimensionless equations to make bankfull channel width and slope the independent variables. This yields equations for predicting dimensional quantities (D_{50}, Q, Q_s, and H) of gravel-bed and sand-bed rivers on any planet given measurements of slope and bankfull width.

We then calibrate and test these relationships on Earth using data from >400 rivers, and find that we predict flow discharges, depths. and bed grain size for gravel rivers to within ~3× for >90% of our dataset, and sediment fluxes to within ~10× for >60%.

Predictions on Mars & Titan: On Mars, we selected two locations where alluvial rivers formed fluvial deposits that are currently being explored in situ by rovers: the Peace Vallis fan in Gale Crater, and the Western Jezero Delta in Jezero Crater (Figure 1d/e).

At Peace Vallis, using previous measurements of the width and slope of channels on the fan[9], we calculate a median bed grain size of 1.8–7.0 cm, which represents a close match to the *Curiosity* measurements. We also make order-of-magnitude estimates for the formation timescale for fan to be ≳0.8–20 Ma, indicating long-lived hydrologic activity around Gale Crater.

At Jezero, we perform similar exercises using published measurements of channel width and slope[8,10]. We find that, unless future rover observations show that the relict channels observed at Jezero are substantially wider or steeper than previous estimates, that the very coarse boulders observed by *Perseverance*[11] occupy a substantial volume of the delta, or that sub-bankfull flows were unexpectedly frequent and sedimentologically significant, the delta requires ≥1 Ma to form.

For Titan, Cassini topographic and imaging data permit measurements of channel slope and width for only two major rivers: Vid Flumina and Saraswati Flumen (Figure 1f/g). Using our own measurements of channel width, and Cassini altimeter measurements of slope, we make estimates similar to those we made for Martian channels. Of interest, at Saraswati Flumen (Figure 1f), we constrain the timescale to form the possible delta found at its terminus to be as short as 10,000 years, indicating it can be formed in a single sea level cycle[2].

The dependence of the hydraulic geometry relationships on gravity, fluid properties, and sediment properties also imply some notable differences among rivers on Earth, Mars, and Titan. Solving the dimensionless equations for dimensional width, depth, slope, and sediment flux, we find expressions for the ratio of bankfull widths, depths, slopes, and sediment fluxes of gravel-bed rivers on any two planetary bodies as a function of the differences in gravity, fluid properties, and sediment properties, for a given discharge and bed grain size.

This predicts that channel width and slope should differ little between Mars and Earth due to the nearly identical fluid and sediment properties and the weak dependence on gravity, which explains why past estimates[8] of flow discharge on Mars based on terrestrial channel width–discharge relationships have yielded plausible values. In contrast, both sand and gravel rivers on Titan, with sediment that is more buoyant than on Earth, should be at least ~3–6× wider and have ~2–5× gentler slopes than analogous terrestrial rivers. These differences arise from Titan's far more buoyant sediment, which can be entrained as bedload or suspended load by shallower flows over gentler slopes. The *Dragonfly* rotorcraft should be able to test these predictions on Titan if it encounters active, or recently active, rivers.

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References: [1] A. Hayes et al. (2017) *Nat. Geo.*, 11, 306-313. [2] O. Aharonson et al. (2009) *Nat. Geo.*, 2, 851-854. [3] B. Ehlmann et al. (2016) *JGR-Planets*, 121, 1927-1961. [4] G. Parker et al. (2007) *JGR*, 112, F04005. [5] G. Parker (2005) *AGU Fall Meeting*. [6] G. Wilkerson, and G. Parker (2011) *J. Hydr. Eng.*, 137, 7. [7] D. Burr et al. (2006) *Icarus*, 181, 235-242. [8] M. Lapotre et al. (2020) *AGU Advances*, 1. [9] M. Palucis et al. (2014) *JGR*, 119, 705-728. [10] T. Goudge et al. (2017) *Icarus,* 301, 58-75. [11] N. Mangold et al. (2021) *Science,* 374, 711-717.